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Paper 4

An Approach to Mathematical Modelling of Ministry of the Environment IHD Representative Basins

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WATER RESOURCES
PAPER 4

AN APPROACH TO MATHEMATICAL MODELLING OF MINISTRY OF THE ENVIRONMENT IHD REPRESENTATIVE BASINS

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PREFACE

As part of the Ministry of the Environment's contribution to the International Hydrological Decade, the River Basin Research Section is carrying out studies of water resources and physical conditions in five basins in Southern Ontario. The basins were selected as being representative of common type areas in the province and the hydrologic studies being undertaken are designed to provide a better understanding of most aspects of the water balance in these areas.

This paper outlines a proposed approach towards the development of mathematical models that will describe the complex interactions of the various components of the hydrologic cycle in each basin. Such models will lead to a better understanding of the actual hydrologic processes that exist and will be useful in the synthesis of hydrologic characteristics in ungauged areas thereby aiding in the solution of water resources problems.

It is anticipated that the compilation of pertinent information and approach outlined in this paper may be helpful to others engaged in the development of mathematical hydrologic models.

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Toronto, November 1, 1972.

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AN APPROACH TO MATHEMATICAL

MODELLING

OF

MINISTRY OF THE ENVIRONMENT

IHD REPRESENTATIVE BASINS

River Basin Research Section
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INTRODUCTION

According to the 'Guidelines for Research Basin Studies', as compiled in 1966 by the Canadian National Committee for the International Hydrological Decade, 'representative basins are areas set aside to permit study of the existing conditions of a region'. One of the objectives of research in these areas is:

> 'To provide data, on all parameters in the hydrologic cycle, so that statistical or physical models may be developed for major climatic and geologic areas. * Principles derived from these models will be used to synthesize the hydrological characteristics of ungauged areas.'

An aim of hydrologic research is to interpret collected data for use in the solution of water management problems. All drainage basin studies should therefore be planned to further the understanding of the hydrologic cycle by using knowledge of the physical and mathematical relationships

* See Appendix I for location maps of basins representative of major climatic and geologic areas in southern Ontario, under study by the River Basin Research Section.

between the various components. The development of 'models' from these relationships should then provide the ability to accurately reconstruct past and present conditions and to predict future events, relating to hydrological phenomena. These models can therefore be useful aids to solving water resources problems dealing with evaluation, design, management and regulation.

Hydrologic Models

Runoff from homogeneous drainage areas and time-variant flows in open channels are affected by factors which are generally known and can be defined explicitly. These factors are difficult to evaluate in a basin-wide study where data are usually scarce and vary both in time and space. However, the analysis of a rainfall-runoff process in a complex drainage basin can be made feasible by the use of models based on concepts of the system. Basin models may be classified into three general categories:

a) physical models,

b) analog models,

c) mathematical models.

In the selection of a type of model, consideration must be given to cost of development, operational problems, accuracy, interpretation of results and subsequent model flexibility.

Physical models are used to represent an idealized physical process or environment and are designed for a specific purpose, at a specific location. Physical models are employed in hydrology to simulate such processes as infiltration, groundwater flow and rainfall-runoff phenomena. With minor modifications,

these models can often be used for extensive periods of time, justifying their cost of construction and operation through the importance of such economic essentials as water-supply, flood control and navigation.

Analog models are commonly used to a varying degree in solving ground-water flow problems. The principle involved in this type of modelling utilizes the analogy between the flow of electricity in an electronic circuit and the flow of water in an aquifer. Analog models, like physical models, are usually designed for a specific location, with the costs being justified primarily on a single-purpose basis.

Mathematical models allow natural hydrologic phenomena to be investigated as systems. The systems approach enables the development of quantitative relationships between the various hydrologic variables which are usually expressed through mathematical formulations (models) for simulation purposes. If the hydrologic variables are considered to follow physical laws rather than laws of probability, the model is described as parametric or deterministic. If laws of probability are considered in characterising the hydrologic variables, the model is described as stochastic or probabilistic.

Parametric Modelling

In preliminary hydrologic studies, parametric models of surface runoff usually related runoff to rainfall and drainage area, and took the form of a purely empirical relationship or of a design procedure following the rational method. With the

increase of knowledge in the mechanics of physical hydrologic processes, modelling techniques become more complex; hence, with a more comprehensive approach, parametric modelling can be treated on the basis of component modelling and integrated system modelling.

(a) Component Modelling:

The overall hydrologic cycle can be divided into several component processes such as precipitation, snowmelt, soil moisture flow, evapotranspiration, direct surface runoff, baseflow and total runoff. Each component or combination of components, may be treated as a separate model. For each model, empirical approximations have been developed to simulate the processes controlling the component(s). However, by gaining an improved understanding of the physical laws governing a component, improvements on the initial empirical models have been achieved whereby the governing concepts underlying the physical situations can be more closely approximated.

(b) Integrated System Modelling:

Through the development of better component models, the overall modelling of the integrated or total system of a watershed has become more complex. Through the use of electronic and digital techniques, the limitations on the complexity are alleviated and the individual component models can be linked to form a comprehensive, integrated system model.

Stochastic Modelling

The approach in stochastic modelling is to present a statistical simulation of a measured response of a system. In order to use effectively a stochastic model, a probability distribution for the input must be determined or assumed. In past hydrologic studies, considerable effort was made to determine the probabilistic properties of hydrologic data, particularly those of streamflow and rainfall.

One of the characteristic features of the stochastic method is that the statistical measures of the hydrologic variables used in the calibration of the model enable probability limits of accuracy to be placed on the simulated values.

OBJECTIVES

The general purpose of this paper is to present the conceptualization in hydrologic modelling relative to present and projected applications to hydrologic investigations in Ministry of the Environment - IHD representative basins. The schematizations developed will serve as flexible frameworks for a subsequent detailed approach and a step-by-step procedure in the development of applicable hydrologic models.

The encompassing objective of the hydrologic simulation studies is to formulate models which possess detailed and specific features which are characteristic of a representative study area. The models that are formulated should possess equally sufficient generality for extrapolation to other study areas or drainage basins within the larger study region. Detailed information, hydrologic and geologic data, compiled for the selected representative basins, are to be used in the optimization of the model parameters and the overall model calibration.

HYDROLOGIC MODELLING

The review of methods, approaches and procedures in hydrologic modelling, which are to be used as bases and guidelines in the development of working models for each of the Ministry of the Environment - IHD representative drainage basins, is summarized in the appendices. These summaries are outlined in a series of figures as model schematizations. The following text serves to introduce briefly the content of each Appendix. Accompanying each Appendix is a further elaboration on the text which serves to explain in more detail the schemes of the respective figures.

These hydrologic modelling procedures are outlined on the basis of:

1. Basic Conceptualization

   exemplified by,

   i) A schematization for functional and inter-related hydrologic processes.

   ii) A schematization for the superposition of basin instrumentation on the functional and inter-related hydrologic processes.

2. Component Models

   exemplified by,

   i) A schematization for hydrologic component models for data generation and simulation.

3. An Integrated Hydrologic System Model
   exemplified by,
   i) A schematization for an integrated (comprehensive) hydrologic system model.
4. A Specific Model Approach
   exemplified by,
   i) A definition scheme for a parametric, linear regression model.
   ii) Expanded definition scheme for a parametric, linear regression model.
   iii) Flow chart for a parametric, linear regression model.
5. A Brief on Stochastic Models
   exemplified by,
   i) A schematization for a type of stochastic hydrologic system model.

Basic Conceptualization

The basic conventional concepts of the hydrologic cycle were used to formulate the schematization of Figure 1 of Appendix II. The functional and inter-related hydrologic processes are outlined by means of a flow scheme showing basically the paths precipitation, as input, would follow through the schematization to the various outputs.

The standard, measured meteorological parameters, precipitation, P, temperature, T, radiation, R, -- (longwave radiation,

R_l, shortwave radiation, R_s, or net radiation, R_n), duration of sunshine, S, humidity, H, wind, W, and Class-A pan evaporation, E_p, are shown as linkages between the source and the processes for which they are a cause or effect, or on which they have an influence directly or indirectly.

The precipitation process resulting in rain and/or snow en route to supply the surface storages, Liquid Amount and Snowpack, is affected by the physical process of Interception which results in a reduction in the total amount available to these surface storages. In the process, an amount is trapped by the vegetal canopy as Interception Storage. The surface storage, Snowpack (snow), is subsequently affected by certain physical interacting processes (heat exchange and melting), resulting in equivalent liquid amounts. The momentary storage at the surface as rainfall amounts and the melt drained from the snowpack are the initializing sources of input to the Soil Profile Storage, a subsurface storage, which is affected by the physical process of Infiltration.

That portion of the initializing input which is in excess of the infiltration requirement, goes to initialize the surface physical process, Surface Runoff (overland flow) by way of satisfying the Depression and Detention Storages. Eventually, amounts from the Depression and Detention Storages, infiltrate to the Soil Profile Storage.

A portion of the supply to the soil profile, normally when in excess of its storage capacity, serves as the source for positive supply to the Aquifer Storage. This contribution is affected by the subsurface physical process of Percolation, which is characterized by a saturated flow. In situations where, and at times when, gravity flow from the soil profile to the water table does not exist, a reverse flow (unsaturated flow) of moisture may be effected by Capillarity; the process being initiated and maintained by a negative gradient set up by the effect of evaporation and/or transpiration at the soil surface.

The Aquifer Storage serves as a source for the active ground-water flow process resulting in Baseflow into the stream. In situations where a local aquifer is in continuum with the expanse of a regional aquifer, a portion of the input to the system may be accounted for as a loss to deep percolation in the regional ground-water flow system.

Total Runoff, the summation of the Surface Runoff and Baseflow, routed by way of channel(s) flow is reproduced at the drainage outlet as a Total Runoff Hydrograph.

Direct losses from the various storages, such as Interception, Depression and Detention, Liquid Amount and Snowpack, are affected by the process of Evaporation. The Transpiration process by plants result in indirect moisture losses from the unsaturated and/or saturated zones. The Evaporation and Transpiration processes form the overall Evapo-transpiration process and the sum of these losses constitute a negative output from the hydrologic system as Actual Evapo-transpiration.

Figure 2 of Appendix II, relates to the various instrumentation and/or methods used for quantitative determination of the various hydrologic variables or parameters in terms of amounts, durations, intensities and frequencies of measurements. For example, the input variable, Precipitation, is sampled for amount, duration, intensity and areal distribution. The instruments used for the sampling being storage gauges and recording and standard rain gauges.

The scheme for each segment in Figure 2 of Appendix II, outlines, in general, the standard instruments used for measurement, the units of measurement and the frequencies of measurement. In cases where there are no standard instruments for use in determining the variable or parameter, the most widely used methods for carrying out these determinations are indicated. For example, surface runoff may be estimated from a total runoff hydrograph by applying one of several hydrograph separation techniques.

Component Models

Figure 3 of Appendix III shows a schematization for component modelling, relating briefly some of the types of models which may be investigated under each component. A 'model', in this context, is used very broadly; that is, it incorporates all operations that result in a historical or synthetic data sequence of the variable. The text on component models in Appendix III consists of a caption for each model and expands

the summarized scheme of Figure 3, quoting examples of references for each type of model, typical data requirements and brief comments on present and projected applications relative to the River Basin Research Section.

The block (Figure 3, Appendix III) for 'Data Management' outlines briefly the necessary and prerequisite operations to be done on the data prior to the development of a component model.

A group of component models may be combined, through a system of transformation ('Transformation System'), to develop an overall comprehensive catchment model. The generated or historical data sequence for each of the component models may form part of the data pool for use in tests for the sensitivity and performance of the overall model developed.

An Integrated System Model

Figure 4 of Appendix IV, shows a schematization for an integrated (comprehensive) hydrologic system model. Outlined are a series of operations through various schemes involving the Precipitation input as rain, or excess snowmelt, which is routed through the various catchment storages, namely, Interception Storage, IS, Surface Storage, SS, Aeration Zone Storage, AZS, Interflow (intermediate) Zone Storage, IZS, and the Saturation Zone Storage, SZS. Routed out of three of the storages are outflow components, namely, Overland Flow, OLF, Interflow, INFL, and Baseflow, BFL. These are subsequently routed into Streamflow through a linear or non-linear reservoir and channel storage or flow translation procedure to produce an

outflow hydrograph Total Runoff, TRO, at the basin outlet. Some of the basic mathematical expressions that relate the various parameters within a given storage function are cited for the intermediary schemes of operations between the input and output. Several explicit relationships have been developed by several investigators and were cited by them to be operational in an integrated system model through empiricisms and numerical approximations. It should be noted, however, that the parameters defined in the various functions have to be determined and optimized on the basis of sufficient physical justifications.

The attached text to Figure 4 of Appendix IV, serves to define the various parameters of the given functions and outlines further, a brief account of the operational sequences throughout the system. It is not the intention at this stage to elaborate on the utilization of these functional relationships, in their explicit forms, in actual numerical or computational procedures.

A Specific Model Approach

Figures 5a to 5c of Appendix V, are representations of basic schemes for a more detailed and specific approach towards a framework for a type of parametric model. Starting from a simple concept and going through some basic definitions, the model is built up to an operating format. Figure 5a of Appendix V, is a definition scheme for a parametric model (Diskin, 1970) for use in an interpretation of a linear regression relationship between precipitation and runoff. Figure 5b

of Appendix V, shows an expansion of the model, taking into consideration implicitly, retention storage and evapc-transpiration. Figure 5c of Appendix V, is the flow chart for the parametric, linear regression model outlined in Figure 5a and 5b of Appendix V. Given is the flow of mathematical operations and computations that may go into the simulation, assuming that the necessary parameters, constants and coefficients (regressions and implied basin characteristics) were previously determined from other regression sub-routines or by other estimating methods. The text on the lumped-parametric model of Appendix V, outlines further, the step-by-step development of the model, with definitions for the various parameters, coefficients and constants, with an explanation of their implied physical significance. Further treatment in the text presents a section on the relative statistical criteria to be used for simplification of the model (e. g. operation in one or two elements) for an appropriate application in the regression sub-routines.

A Brief on Stochastic Models

Figure 6 of Appendix VI, shows a framework for a stochastic hydrologic systems model (Chow and Kareliotis, 1970), outlining schematically the inter-relationship (formulated on the principle of conservation of mass) among the individual models, each of which is a component stochastic model. A very long sequence of historical record is required for each time series in order to adequately determine its probability distribution, or to

determine by correlogram or spectral analysis, the type of stochastic model (autocorrelation, harmonic, moving average, etc.) to be used in the generating processes. The text of Appendix VI gives a short review on an approach to stochastic hydrologic system modelling.

APPLICATION

The review on conceptual hydrologic modelling outlines broadly the extent to which the River Basin Research Section plans to proceed with the formulation (building and calibration) of a hydrologic model for each of the Ministry of the Environment - IHD representative drainage basins.

The literature reviewed indicates that not many successful attempts have been made to formulate one overall hydrologic system model which has a general application to all types of drainage basins and hydrologic situations. However, the principles and approaches that have been developed from the application of modelling to more specific conditions, provide for the selection of an approach that may be transposed to areas with similar, basic hydrologic characteristics.

The emphasis in modelling has been on separate hydrologic phases (component models). Component modelling, theoretically, requires a substantial amount of information and lengthy sequences of data for a meaningful approach towards formulating a simulator. Also, long sequence of record is required for a totally effective calibration of the model. The problem of lack of sufficient data and length of records, however, is often alleviated by making implicit or explicit assumptions regarding a parameter, group of parameters and/or some aspects of the inter-reacting hydrologic processes. These assumptions are often desirable for simplification of the model to make it computationally tractable.

The present extent of the instrumentation in the River Basin Research Section's drainage basins and the degree of data collection activity, relative to the length of historical record of the various hydrologic and geologic variables compiled to date, will necessarily dictate the nature and types of hydrologic modelling that can be attempted. The relatively short sequences of data collected subject the choice of models to the confines of parametric and deterministic types and of a water balance analysis or accounting approach. Attempts can be made as first approximations, at model calibration through parameter optimizations, based on averages, ratio estimates or least-square methods.

For the present time, component modelling will be restricted to manipulations with the parametric and deterministic types, on the basis of tried approaches and existing modelling techniques. Knowledge gained from the insight into and/or trials with existing model techniques will be used in the eventual formulation of an overall comprehensive catchment model, based on the data from one or more of the representative basins.

Although cursory and trial attempts will be made with a modelling exercise based on conventional probabilistic treatments, no extensive attempts will be made at this stage with stochastic modelling due to the lack of extensive data for each component time series. Although long series of records are a prerequisite for effective utilization of this approach to modelling, attempts

may be made to formulate and test simpler existing models, e.g., the formulation of a precipitation model generator (Grace & Eagleson, 1967; Perkins, 1971), by utilizing relatively short sequences of recording precipitation data to develop a stochastic model for generating short-time-interval sequences of rainfall data.

Current activities in the Section are centred around data management (data reduction, compilation,error analysis, etc.) which is a prerequisite for a rational and concerted approach towards overall water balance analyses and hydrologic modelling. Models will initially be of a parametric type, based largely on the framework set out in the definition scheme for a parametric, linear regression model. Subsequently a more detailed approach will be followed, as outlined for an integrated hydrologic system model, as shown in Appendix IV.

SELECTED BIBLIOGRAPHY

Amorocho, J. and Orlob, G., 1961. 'Non-linear Analysis of Hydrologic Systems'. University of California, Water Resources Centre, Contribution No. 40.

Amorocho, J. and Orlob, G., 1961. 'An Evaluation of Inflow-Runoff Relationship in Hydrologic Studies'. University of California, Water Resources Centre, Contribution No. 41.

Amorocho, J. and Espildora, B., 1966. 'Mathematical Simulation of the Snow Melting Processes'. Department of Water Science and Engineering, University of California, Davis, W.S.E. Paper 3001.

Amorocho, J., 1967. 'The Non-linear Prediction Problem in the Study of Runoff Cycle'. Water Resources Research, Vol. 3 (3): 861 - 880.

Anderson, E. A. and Crawford, N. H., 1964. 'The Synthesis of Continuous Snowmelt Runoff Hydrographs on Digital Computer'. Department of Civil Engineering, Stanford University, Technical Report No. 26.

ARS - U. S. Department of Agriculture. 'Pending U. S. DAHL - 70 Model of Watershed Hydrology'. Tech. Bull. No. 1435.

Baier, W. and Robertson, G., 1965. 'A New Versatile Soil Moisture Budget'. Canadian Journal of Plant Science, Vol. 46: 229 - 315.

Baier, W., 1969. 'Concepts of Soil Moisture Availability and their Effects on Soil Moisture Estimates from Meteorological Budget'. Canadian Journal of Plant Science, Vol. 6: 165 - 178.

Beard, L. R., 1965. 'Use of Inter-related Records to Simulate Streamflow'. ASCE - Jour. of Hydr. Div., Vol. 91 (5): 113 - 22.

Beard, L. R., 1967. 'Simulation of Daily Streamflow'. Int. Hydro. Symp.,Ft. Collins, Vol. 1: 624 - 632.

Bechir, M. H., et al., 1967. 'Effect of Basin Morphology on Response to Flood Flows'. Int. Hydrol.Symp., Ft. Collins, Vol. 1: 46 - 56.

Becker, A., 1967. 'Threshold Consideration and their General Importance for Hydrologic System Investigation'. Int. Hydrol. Symp., Ft. Collins, Vol. 1: 94 - 102.

Bell, F. C., 1967. 'An Alternative Physical Approach to Watershed Analysis and Streamflow Estimation'. Int. Hydrol. Symp., Ft. Collins, Vol. 1: 86- 93.

Benson, M. A. and Matalas, N. C., 1967. 'Synthetic Hydrology Based on Regional Statistical Parameters', Water Resources Research, Vol. 3 (4): 931 - 935.

Boughton, W. C., 1968. 'A Mathematical Catchment Model for Estimating Runoff'. Jour. of Hydrol., Vol. 7 (2):

Bowman, D. and King, K., 1965. 'Determination of Evapotranspiration using Neutron Scattering Method'. Canadian Journal of Soil Science, Vol. 45: 117 - 126.

Brakensiek, D. L. and Onstad, C. A., 1968. 'The Synthesis of Distributed Inputs for Hydrograph Predictions'. Water Resources Research, Vol. 4 (1): 79 - 85.

Caffey, J. E., 1965. 'Regional Correlation in Annual River Flow and in Annual Precipitation'. Hydrology Papers No. 6, Colorado State University, Ft. Collins.

Carlson, C. A., et al.,1956. 'Predicting Moisture in the Surface Foot of Soil'. Soil Sc. Soc. of Amer. Proc. 20: 412 - 415.

Chapman, T. G., 1971. 'Optimization of a Rainfall-Runoff Model for an Arid Zone Catchment'. Symp. on the Result of Research on Representative Experimental Basins; IASH Publ. No. 96.

Charbonneau, R., et al., 1971. 'Precision and Sensitivity of Parametric Models'. 8th Canadian Hydrology Symp., Vol. I: 200 - 224, Quebec City.

Chidley, T. 'A New Method of Investigation for River Recession Curves'. Div. Lib. Authors File.

Chow, V. T. and Kareliotis, S. J., 1970. 'Analysis of Stochastic Hydrologic Systems'. Water Resources Research, Vol. 6 (6): 1569 - 1582.

Chow, V. T. and Ramasseshan, S., 1965. 'Sequential Generation of Rainfall and Runoff Data'. ASCE - Jour. of Hydr. Div. 91 (4): 204 - 223.

Christiansen, J. E., 1966. 'Estimating Pan Evaporation and Evapotranspiration from Climatic Data'. Utah W. R. Lab.

Claborn, B. J. and Moore, W. L., 1970. 'Numerical Simulation of Watershed Hydrology'. Tech. Report to the office of WRR: Dept. of the Interior - Hydr. Eng. Lab., Dept. of Civil Eng., University of Texas - Hydr. 14 - 7001, CRX1R-54.

Corps. of Eng. U. S. Army, 1971. 'Runoff Evaluation and Streamflow Simulation by Computer'. A U. S. contribution to IHD. U. S. Army Eng. Div. N. Pacific Corps. of Eng., U. S. Army, Portland, Oregon.

Crawford, N. H. and Linsley, R. K., 1966. 'Digital Simulation in Hydrology: Stanford Watershed Model IV'. Dept. of Civil Eng., Stanford University, Technical Report No. 39.

Dawdy, D. R., Kalinin, G. P., 1969. 'Mathematical Modelling in Hydrology'. A report prepared on behalf of the Committee in Mathematical Models in Hydrology, as a report of the IASH to the Mid-Decade Conferences of the International Hydrological Decade.

Deboer, D. W. and Johnson, H. P., 1969. 'Development of Mathematical Model for the Simulation of Flatland Watershed Hydraulics'. Iowa State Water Resources Research Inst., Iowa State University, PB - 188793.

Diskin, M. H., 1970. 'Definition and Uses of the Linear Regression Model'. Water Resources Research, Vol. 6 (6): 1668 - 1673.

Diskin, M. H., 1967. 'A Dispersion Analog Model for Watershed Systems'. Int. Hydrol. Symp., Ft. Collins, Vol. 1: 38 - 45.

Dooge, J. C., 1967. 'The Hydrologic Cycle as a Closed System'. Int. Hydrol. Symp., Ft. Collins, Vol. 2: 98 - 113.

Dooge, J. C., 1959. 'A General Theory of Unit Hydrograph'. Jour. Geophys. Res. AGU, Vol. 64 (2): 241 - 256.

Eagleson, P. S., 1962. 'Unit Hydrograph Characteristics for Sewered Areas'. Proc. ASCE - Jour. of Hydr. Div., Vol. 88 HY2: 1 - 25.

Eagleson, P. S., et al., 1965. 'The Computation of Optimum Realizable Unit Hydrographs for Rainfall and Runoff Data'. Hydrodynamic Lab. Report No. 84, M.I.T.

Eagleson, P. S., 1967. 'A Distributed Linear Model for Peak Catchment Discharge'. Int. Hydrol. Symp., Ft. Collins, Vol. 1: 1 - 8.

Farvolden, R. N., 1963. 'Geologic Controls on Ground-Water Storage and Baseflow'. Jour. of Hydrol.: 219 - 249.

Fiering, M. B., 1964. 'A Markov Model for Low-Flow Analysis', IASH, Vol. 9 (1): 37 - 47.

Foster, G. R., et al., 1968. 'Simulation of Overland Flow on Short Field Plots'. Water Resources Research, Vol. 4 (6): 1179 - 1187.

Franz, D. D., 1971. 'Hourly Rainfall Synthesis for a Network'. ASCE - Jour. of Hydr. Div., HY9: 1349 - 1365.

Freeze, R. A. and Witherspoon, P. A., 1967. 'Theoretical Analysis of Regional Ground-Water Flow - Effect of Water-Table Configuration and Subsurface Permeability Variation'. Water Resources Research, Vol. 3 (2): 623 - 634.

Furness, L. W. and Busby, M. W., 1969. 'Two Methods of Estimating Baseflow at Ungauged Stream Sites in Kansas and Adjacent States'. Geo. Survey Research, Prof. Paper 575-C: C208 - C211.

Gannon, J., 1963. 'Definition of River Drought Flow Characteristics'. Bull. IASH Vol. 8.

Gay, L. W., 1970. 'Energy Balance Estimates of Evapotranspiration'. Inst. of Water Studies in Oregon Seminar W. R. 012,69.

Grace, B. A. and Eagleson, P. S., 1967. 'A Model for Generating Synthetic Sequences of Short-Time Interval Rainfall Depths'. Proc. Int. Hydrol. Symp., Ft. Collins, Vol. 1: 268- 276.

Gray, D. M., 1961. 'Synthetic Unit Hydrograph for Small Watersheds'. ASCE - Jour. of Hydr. Div., 87 (4): 33 - 54.

Gumbel, E. J., 1963. 'Statistical Forecast of Droughts'. Bull. IASH, Vol. 8: 5 - 23.

Hamon, W. R., 1966. 'An Equation for Estimating Potential Evapotranspiration in terms of temperature function and day length. - Methods for Estimating Evapotranspiration'. Irr. and Dr. Speciality Conference, Las Vegas, ASCE: 235 - 36.

Hargreaves, G. H., 1966. 'Consumptive use Computation from Evaporation Pan Data - Methods for Estimating Evapotranspiration'. Irr. and Dr. Speciality Conference, Las Vegas, ASCE: 35 -62.

Hiemstra, L. and Creese, R., 1970. 'Synthetic Generation of Seasonal Precipitation'. Jour. of Hydrol., Vol. 11 (1): 30 - 46.

Huggins, L. F. and Monke, E. J., 1970. 'Mathematical Simulation of Hydrologic Events of Ungauged Watershed'. Purdue University, Water Resources Centre, Lafayette, Indiana - Tech. Report 14.

Huggins, L. F. and Monke, E. J., 1968. 'A Mathematical Model for Simulating Hydrologic Response of a Watershed'. Water Resources Research, Vol. 4: 529 - 540.

Ibbitt, R. P., et al., 1971. 'Fitting Methods for Conceptual Catchment Models'. ASCE - Jour. of Hydr. Div., HY9: 1331-1341.

Kayoda, M., 1967. 'Analysis of Ground-Water Flow and Rainfall Loss'. Int. Hydrol. Symp., Ft. Collins, Vol. 1: 177 - 184.

Kiraly, L., 1971. 'Ground-Water Flow in Heterogeneous, Anisotropic Fractured Media: A Simple Two-Dimensional Electric Analog'. Jour. of Hydrol., Vol. 12 (3): 255 - 261.

Larson, C. L., 1965. 'A Two Phase Approach to the Prediction of Peak Rates and Frequencies of Runoff for Small Ungauged Watersheds'. Stanford University Tech. Report No. 53.

Laurenson, E. M., 1964. 'A Catchment Storage Model for Runoff Routing'. Jour. of Hydrol. No. 2: 141 - 163.

Ligon, J. T., et al., 1965. 'Procedure for Estimating Occurrence of Soil Moisture Deficiency and Excess'. Trans. ASAE, Vol. 8: 219 - 222.

Luthin, J. N., 1957. 'Drainage of Agricultural Lands'. Am. Soc. of Agronomy, Madison.

Machmeier, R. E. and Larson, C. L., 1967. 'A Mathematical Routing Model'. Int. Hydrol. Symp., Ft. Collins, Vol. 1: 64 - 71.

McMillan, W. D., 1966. 'Theoretical Analysis of Ground-Water Basin Operations'. Water Res. Centre Contrib. No. 114, Hydraulic Lab., University of California.

Matalas, N. C., 1963. 'Probability distribution of low flows'. USGS Prof. Paper 434-A.

Meyboom, P., 1961. 'Estimating Ground-Water Recharge from Streamflow Hydrograph'. Jour. Geophy. Research, Vol. 66 (4).

Mitchell, W. D., 1967. 'Linear Analysis of Hydrographs'. Water Resources Research, Vol. 3 (3): 891 - 895.

Morton, F. I., 1971. 'Catchment Evaporation and Potential Evapotranspiration - Further development of a climatologic relationship'. Jour. of Hydrol.,Vol. 12 (2): 81 - 99.

Moreau, D. H. and Pyatt, E. E., 1970. 'Weekly and Monthly Flows in Synthetic Hydrology'. Water Resources Research, Vol. 6 (1): 53 - 61.

Mukammal, E. and Bruce, J., 1960. 'Evaporation Measurements by Pan and Atmometer'. Met. Branch, Dept. of Transport, Cir. 3300, Tec. 315.

Narayana, V. and Riley, J., 1971. 'Simulation of Runoff from Urban Watershed'. Water Res. Bull., Vol. 7 (1): 54 - 68.

Nash, J. E., 1957. 'The Form of Instantaneous Unit Hydrograph'. IASH Publ. 45, Vol. 3: 114 - 121.

O'Connell, P. E., et al., 1970. 'River Flow Forecasting Through Conceptual Models. Part II - The Brosha Catchment at Febrane'. Jour. of Hydrol. 10: 317 - 329.

Overton, D. E., 1967. 'Analytical Simulation of Watershed Hydrographs from Rainfall'. Int. Hydrol. Symp., Ft. Collins, Vol. 1: 9 - 12.

Overton, D. E., 1964. 'Mathematical Refinement of an Infiltration Equation for Watershed Engineering'. U. S. Dept. of Agr., ARS: 41 - 99.

Pattison, A., 1965. 'Synthesis of Hourly Rainfall Data'. Water Resources Research Vol. 1 (4): 489 - 497.

Payne, K. and Newman, W. R., 1969. 'Daily Streamflow Simulation'. ASCE - Jour. of Hydr. Div., HY4: 1163 - 1179.

Perkins, F. E., 1971. 'Simulation Models - Simulation of Water Resources Systems (Institute II)'. Nebraska Water Resources Institute, University of Nebraska.

Pinder, G. F. and Jones, J. F., 1969. 'Determination of Ground-Water Component of Peak Discharge from Chemistry of Total Runoff'. Water Resources Research, Vol. 5 (2): 438-445.

Prasad, R., 1967. 'A non-linear Hydrological System Response Model'. ASCE - Jour. of Hydr. Div., Vol. 93 (HY4): 201 - 221.

Quick, M. C., 1971. 'Experiments with Physical Snowmelt Models'. 8th Canadian Hydrol. Symp., Vol. I: 131 - 150, Quebec City.

Quimpo, R. G., 1967. 'Stochastic Model of Daily River Flow Sequences'. Colorado State Univ., Hydrology Paper No. 18.

Raudkivi, A. J. and Lawgun, N., 1970. 'Synthesis of Urban Rainfall'. Water Resources Research, Vol. 6 (2): 455 - 464.

Reich, B.M., 1970. 'Flood Series Compared to Rainfall Extremes'. Water Resources Research, Vol. 6 (6): 1655- 1667.

Robb, D. C., 1966. 'Consumptive use Estimates for Solar Radiation and Temperature - Methods for Estimating Evapotranspiration'. Irr. and Dr. - Speciality Conference, Las Vegas, ASCE: 169 - 191.

Roesner, L. A. and Yeidjevich, V. M., 1966. 'Mathematical Models, for Time Series of Monthly Precipitation and Monthly Runoff'. Colorado State Univ. Hydrology Paper No. 15.

Sarma, P. B. S., Delleur, J. W. and Rao, A. R., 1969. 'A Program in Urban Hydrology Part II - An Evaluation of Rainfall - Runoff Models for Small Urbanized Watersheds and Effect of Urbanization on Runoff'. Purdue Univ., Water Resources Research Centre, Tech. Rep. No. 9.

Schemer, F. A., 1969. 'Investigation of a Linear Model to Describe Hydrologic Phenomena of Drainage Basins'. W. R. Inst., Texas A & M Univ., Tech. Rep. No. 19.

Schulz, E. F. et al., 1971. 'Comparison of Dimensionless Unit Hydrographs in Thailand and Taiwan'. Nordic Hydrology II: 23 - 46.

Schweig, Z. and Cole, J. A., 1968. 'Mathematical Model of Runoff'. Water Research Assoc., Tech. Memo TM 44.

Searcy, J. K., 1959. 'Flow-duration Curves'. USGS Water Supply Paper 1542 -A.

Shahbazi, M. and Todd, D. K., 1967. 'Analytic Techniques for Determining Ground-Water Flow Fields'. Water Resources Centre Contrib. No. 117, Hydraulic Lab., University of California.

Shane, R. M. and Lynn, W., 1964. 'Mathematical model for flood risk evaluation'. ASCE - Jour. of Hydr. Div., Vol. 90, HY 6: 1 - 20.

Shane, R. M. and Gaver, D. P., 1970. 'Statistical Decision Theory Techniques for Revision of Mean Flood Flow Regression Estimates'. Water Resources Research, Vol. 6 (6): 1649 - 1654.

Singh, K. P., 1964. 'Non-linear Instantaneous Unit Hydrograph Theory'. Proc. ASCE - Jour. Hydr. Div., Vol. 90, No. HY2: 313 - 347.

Singh, K. P., 1968. 'Some Factors Affecting Baseflow'. Water Resources Research, Vol. 4 (5): 985 - 999.

Sittner, W. T., et al., 1969. 'Continuous Hydrograph Synthesis with an API-Type Hydrologic Model'. Water Resources Research, Vol. 5 (5): 1007 - 1022.

Skaggs, R. W., et al., 1969. 'Experimental Evaluation of Infiltration Equations'. Trans. ASAE., Vol. 12 (6): 822 - 828.

Skaggs, R. W., et al., 1970. 'An Approximate Method for Determining the Hydraulic Conductivity of Unsaturated Soil'. Purdue Univ., WRR Centre, Tech. Rep. 11.

Smart, J. S. and Surkan, A. J., 1967. 'The Relation between Main Stream Length and Area in Drainage Basin'. Water Resources Research, Vol. 3 (4): 963 - 974.

Snyder, F. F., 1958. 'Synthetic Flood Frequency'. ASCE - Jour. Hydr. Div., 84 (5): 1808-1 - 1808-22.

Stallman, R. V., 1956. 'Use of Numerical Methods for Analyzing Data on Ground-Water Levels'. Symposia Darcy, IASH Pub. 41, 227 - 231.

Stearn, F. W. and Carlson, C.A., 1960. 'Correlation between Soil Moisture Depletion Solar Radiation and other Environmental Factors'. Jour. Geophys. Res. 65: 3727 - 3732.

Sutcliffe, J. V., 1966. 'The Assessment of Random Errors in Areal Rainfall Estimation'. IASH - Bull. 11, ANEE No. 3: 35 - 42.

Svandize, G. G.,1967. 'River Runoff as a Stochastic Process and its Mathematical Modelling'. Int. Hydrol. Symp., Ft. Collins, Vol. 1: 329 - 336.

Taylor, A. B. and Schwarz, H. E., 1952. 'Unit Hydrograph Lag and Peak Flow Related to Basin Characteristics'. Trans. Amer. Geophys. Union, Vol. (33), No. 2: 235 - 246.

Todorovic, P. and Zelenhasic, E., 1970. 'A Stochastic Model for Flood Flow Analysis'. Water Resources Research, Vol. 6 (6): 1641 - 1648.

Toth, J. A., 1963. 'A Theoretical Analysis of Ground-Water Flow in Small Drainage Basins'. Jour. Geophys. Research, Vol. 68 (16): 4795 - 4812.

Toth, J. A., 1962. 'A Theory of Ground-Water Motion in Small Drainage Basins in Central Alberta, Canada'. Jour. Geophy. Research 67 (11): 4375 - 4387.

Trainer, F. W., 1969. 'Drainage Density as an Indicator of Baseflow in Part of Potomac River Basin'. USGS - Prof. Paper 650C: C177 - C183.

Trainer, F. W., 1969. 'Precipitation and Base Runoff, Big Pipe Creek, Maryland'. USGS - Prof. Paper 650D: D222 - D227.

U. S. Army Corps of Eng., 1960. 'Runoff from Snowmelt'. EM1110 - 2-1406, U. S. Gov't. Printing Office, Washington.

Viessman, W., 1968. 'Runoff Estimation for very Small Drainage Areas'. Water Resources Research, Vol. 4 (1): 87 - 93.

Visser, W. C., 1966. 'Unsaturated Soil Moisture Conditions Studied from Field Observations'. IASH - Proc. of Wageningen Symp., 952 - 966.

Watt, W. E. and Hsu, C. T., 1971. 'Continuous Basin Snowmelt Runoff Simulation'. 8th Canadian Hydrol. Symp., Vol. II, Quebec City.

Wooding, R. A., 1965. 'A Hydraulic Model for Catchment Stream Problem: I. Kinematic Wave Theory'. Jour. of Hydrol., Vol. 3:

Wooding, R. A., 1966. 'A Hydraulic Model for the Catchment Stream Problem: III Comparison with Runoff Observation'. Jour. of Hydrol., Vol. 4: 21 - 37.

Zahner, R., 1967. 'Refinement in Empirical Functions for Realistic Soil Moisture Regime under Forest Cover'. Int. Symp. on Forest Hydrology, Symp. Publ. Div., Pergamon Press: 261 - 274.

APPENDIX I

IHD PROJECT REPORTS

East & Middle Oakville Creeks
IWB - RB - 16; ONT - 4

Venison Creek
IWB - RB - 17; ONT - 4

Blue Springs Creek
IWB - RB - 18; ONT - 4

Bowmanville, Soper & Wilmot Creeks
IWB - RB - 19; ONT - 4

Wilton Creek
IWB - RB - 20; ONT - 4

Location and Instrumentation Maps of

Ministry of the Environment-

IHD Representative Basins

(in pocket at back of report)

IHD PROJECT REPORT

Project Title: Representative Basin Studies - East and Middle Oakville Creeks.

File Reference: IWB - RB - 16; ONT - 4

Objectives: Collection of hydrologic and geohydrologic data necessary for the study of all aspects of the hydrologic regime and the general water balance in a basin representative of clay and clay till plains in southern Ontario.

Instrumentation: 5 recording and 3 non-recording streamflow gauging stations; 1 main meteorological station, 6 satellite meteorological stations; 2 recording, ground-water observation wells; 21 peizometers in 8 nests, 12 private, non-recording, shallow, ground-water observation wells, 9 snow courses and 12 soil moisture index stations.

IHD PROJECT REPORT

Project Title: Representative Basin Studies - Wilton Creek

File Reference: IWB - RB - 20; ONT -4

Objectives: Collection of hydrologic and geohydrologic data necessary for investigations into all phases of the general water balance in a basin representative of limestone conditions in southern Ontario.

Instrumentation: 2 recording and 2 non-recording streamflow gauging stations; 2 main meteorological stations and 5 satellite meteorological stations; 4 recording, ground-water observation wells and 11 piezometers in 4 nests.

IHD PROJECT REPORT

Project Title: Representative Basin Studies - Bowmanville, Soper and Wilmot Creeks

File Reference: IWB - RB - 19; ONT - 4

Objectives: Collection of hydrologic and geohydrologic data necessary for the study of all aspects of the hydrologic regime and general water balance in a basin representative of moraine, till and clay areas in southern Ontario.

Instrumentation: 16 recording and 2 non-recording streamflow gauging stations; 2 main meteorological stations and 12 satellite meteorological stations; 12 recording ground-water observation wells; 17 piezometers in 8 nests; 23 private, shallow, non-recording ground-water observation wells; 16 soil moisture index stations; 2 ground-temperature recorders and 12 snow courses.

IHD PROJECT REPORT

Project Title: Representative Basin Studies - Venison Creek

File Reference: IWB - RB - 17; ONT - 4

Objectives: Collection of hydrologic and geohydrologic data necessary for the study of all aspects of the hydrologic regime and general water balance in a basin representative of sand plain conditions in southern Ontario.

Instrumentation: 3 recording and 1 non-recording streamflow gauging stations; 1 main meteorological station and 3 satellite meteorological stations; 4 recording, ground-water observation wells and 3 piezometers in 1 nest.

IHD PROJECT REPORT

Project Title: Representative Basin Studies - Blue Springs Creek

File Reference: IWB - RB - 18; ONT - 4

Objectives: Collection of hydrologic and geohydrologic data necessary for the study of all aspects of the hydrologic regime and general water balance in a basin representative of kame, till and bedrock conditions in southern Ontario.

Instrumentation: 3 recording and 6 non-recording streamflow gauging stations; 5 recording ground-water observation wells; 11 piezometers in 3 nests and 8 private, non-recording, shallow ground-water observation wells.

APPENDIX II

HYDROLOGIC MODEL:

Basic Conceptualization

Figure 1 shows the schematization outlining the functional and inter-related processes based on the conventional concepts of the hydrologic cycle.

The end product of the meteorological process, Precipitation, is rain and/or snow, a portion of which is intercepted by the vegetal canopy as Interception Storage and eventually lost to Evaporation (or Sublimation). Precipitation as a liquid is held momentarily at the ground surface as Detention Storage. Some, through the process of Infiltration, enters the Unsaturated Zone and that in excess of the soil moisture capacity goes to replenish the local ground-water flow system (Saturated Zone) by Percolation. Precipitation with rates in excess of the infiltration capacity at the soil surface contributes to Total Runoff by way of direct Surface Runoff. A portion of the precipitation to direct Surface Runoff is trapped as Depression Storage in ponds, swamps, etc. Subsequently, this retained portion of the runoff contributes respectively to Evaporation, to Infiltration to the Soil Profile and recharge to the local Aquifer. Portions of the recharge eventually contribute as Baseflow to Total Runoff and to Regional Flow as Deep Percolation. Eventually, there may be a reverse flow to the Unsaturated Zone as a result of a capillary (suction) potential set up by Evaporation and/or Transpiration at the soil surface.

Precipitation which occurs as snowfall is stored on the ground as Snowpack. The pack undergoes various forms of metamorphosis prior to the active snow-melting process. During the metamorphosis phase, a quantity of moisture is lost to Evaporation (by Sublimation); also during this period, several phases of heat exchange take place at the snowpack-soil interface and between the snowpack and the liquid rain. These and several other types of energy fluxes (Radiation, Temperature) influence the onset of the Snowmelt process by way of convective heat transfer between the pack and atmosphere. The Snowmelt, as liquid excess drained from the Snowpack, follows a similar path to that of the rain; that is, via Depression and Detention Storages and Infiltration, and subsequently to Surface Runoff and Baseflow to Total Runoff which are reproduced as a Total Runoff Hydrograph at the basin outlet.

Transpiration by crops from the Unsaturated and/or Saturated zones, together with evaporation from the various processes (Interception, Snowpack, Detention and Depression storages), contributes to the Actual Evapotranspiration, from the basin.

The ancilliary meteorological variable Temperature, T, is associated with Radiation, R, (as longwave, shortwave or net radiation), with net energy (heat) flux at the incident surface. The Humidity, H, is a function of the vapour pressure, e_a and the saturated vapour pressure, e_s, at a given air temperature. The Wind, W, is expressed in terms of the wind speed, u, and direction. Sunshine duration, S, is directly related to the temperature and shortwave radiation variables. These ancilliary meteorological variables are necessary prerequisites for use in computation (through empirical formulae) of snowmelt and evaporation from snowpack and evaporation from available sources of free water.

Instrumentation

Figure 2 shows the various instrumentations and/or methods used for quantitative determination of the various hydrologic variables or parameters.

The rainfall is measured by standard rain gauges, RS, providing total depth quantities in inches, arranged to yield daily, monthly and yearly summaries. Rainfall intensities and durations are measured by recording rain gauges, RA, providing summaries of storm amount, duration and rates per unit time which are the data necessary for such analytical procedures as storm intensity-frequency and depth-area-duration analyses. Snowfall may be measured accumulatively with Alter-shielded or Nipher-shielded storage gauges; accumulated snowfall on the ground as snowpack is core-sampled for depth, water equivalent and density.

The other meteorological variables are measured by conventional instruments: temperature extremes by maximum and minimum thermometers; humidity and temperature by hygrothermographs; duration of sunshine by Campbell-Stokes solarimeters; longwave and shortwave (Solar) radiation by Eppley or Kipp pyranometers; net radiation by CSIRO pyrradiometers; evaporation by Class-A pans and wind speed by anemometers.

Interception (amount of precipitation intercepted by the vegetation) may be determined by plot studies, or estimated with the use of existing, general empirical equations.

Snowmelts are usually determined by computations from snowmelt indices and/or with general empirical equations. In the synthesis of snowmelt hydrographs, some basic factors have to be determined. These are areal extent of snow cover; snowpack parameters with respect to depth, water equivalent, temperature and free water; the variation of these parameters with elevation; albedo of the snow surface; and the critical sequence of factors affecting melt such as melt rate and loss and runoff conditions of the basin.

The extent of the depression storage capacity and its distribution may be determined from topographic maps and field surveys of the drainage area.

The infiltration function may be approximated by empirical procedures such as sample plot studies (infiltrometer, rain-ulators), or by laboratory experiments with field soil samples.

A time series of soil moisture data may be determined by thermogravimetric analyses of field samples or monitored in situ by tensiometers or electrical resistance block methods or by the nuclear (neutron meter) method, etc. Soil temperature profiles may be monitored in situ by thermohms or by ground-temperature recorders. The necessary soil moisture characteristics, (soil moisture-hydraulic conductivity and soil moisture-tension curves), for describing the unsaturated flow, may be determined through laboratory experiments on specific soil samples.

Aquifer characteristics (hydraulic conductivity, transmis-sibility) may be determined by pumping tests and by analytical techniques using ground-water level fluctuations in observation wells and piezometers. The saturated hydraulic conductivity characterizes the rate of percolation.

Total runoff may be determined by the use of conventional streamflow gauging stations (recording gauges with natural controls, NR, or artificial controls, AR and staff gauges, NN). Measured stages at each gauge are converted to continuous discharge as mean daily flows in cubic feet per second, with the use of empirically developed stage-discharge rating curves.

Baseflow and direct surface runoff may be determined by analytical methods such as hydrograph separation. A direct estimate of baseflow from some areas may be determined by the measurement of spring discharges.

Estimates of the potential evapotranspiration may be obtained from adjusted evaporation pan measurements or estimated with the use of existing empirical formulae. Estimates of actual evapotranspiration may be obtained from lysimeter studies or from adjusted potential evapotranspiration with a crop consumptive-use factor determined from land-use studies.

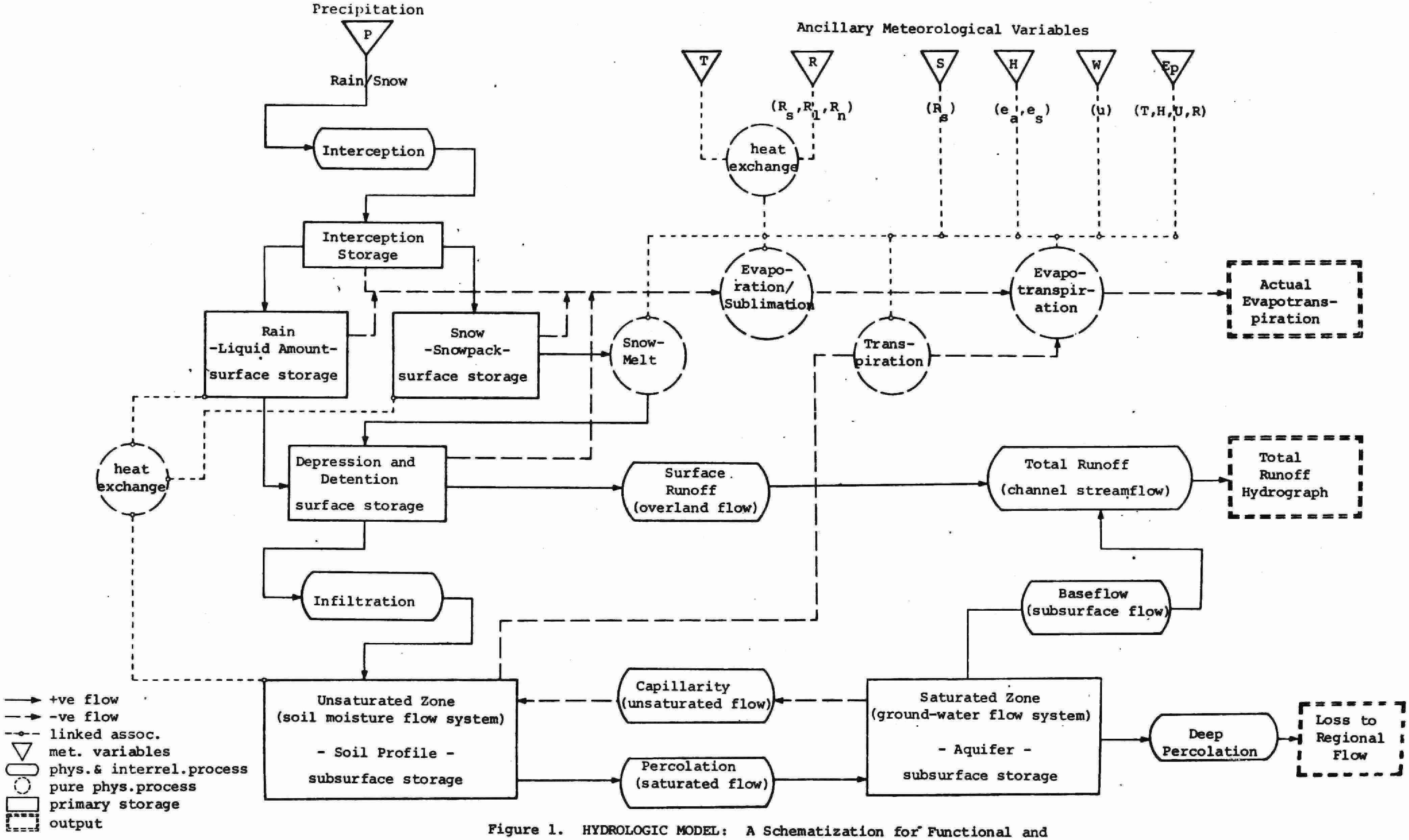
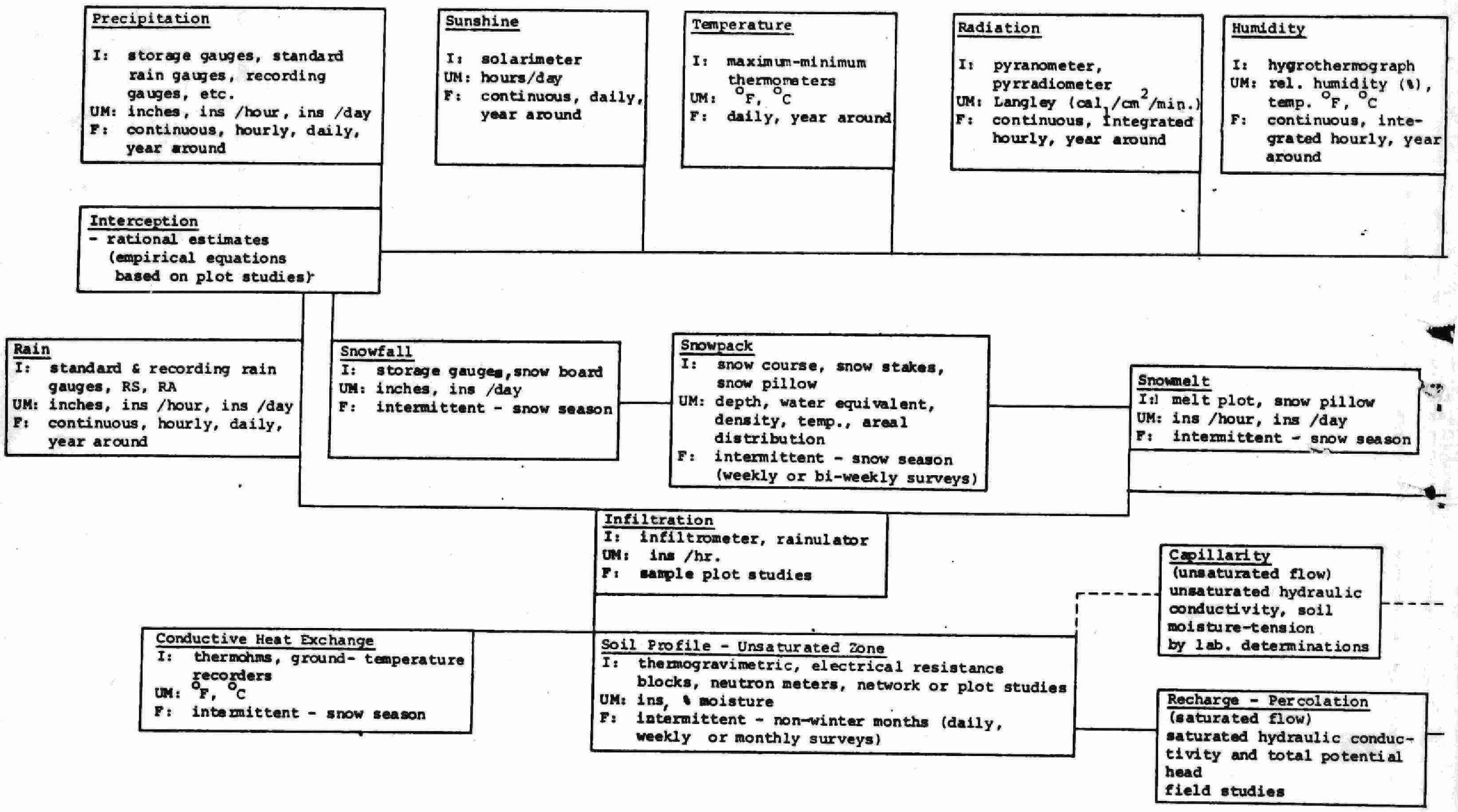


Figure 1. HYDROLOGIC MODEL: A Schematization for Functional and Inter-related Hydrologic Processes


Precipitation
I: storage gauges, standard rain gauges, recording gauges, etc.
UM: inches, ins /hour, ins /day
F: continuous, hourly, daily, year around
Sunshine
I: solarimeter
UM: hours/day
F: continuous, daily, year around
Temperature
I: maximum-minimum thermometers
UM: °F, °C
F: daily, year around
Radiation
I: pyranometer, pyrradiometer
UM: Langley (cal./cm²/min.)
F: continuous, integrated hourly, year around
Humidity
I: hygrothermograph
UM: rel. humidity (%), temp. °F, °C
F: continuous, integrated hourly, year around
Interception
- rational estimates (empirical equations based on plot studies)
Rain
I: standard & recording rain gauges, RS, RA
UM: inches, ins /hour, ins /day
F: continuous, hourly, daily, year around
Snowfall
I: storage gauges, snow board
UM: inches, ins /day
F: intermittent - snow season
Snowpack
I: snow course, snow stakes, snow pillow
UM: depth, water equivalent, density, temp., areal distribution
F: intermittent - snow season (weekly or bi-weekly surveys)
Snowmelt
I: melt plot, snow pillow
UM: ins /hour, ins /day
F: intermittent - snow season
Infiltration
I: infiltrometer, rainulator
UM: ins /hr.
F: sample plot studies
Capillarity
(unsaturated flow)
unsaturated hydraulic conductivity, soil moisture-tension
by lab. determinations
Conductive Heat Exchange
I: thermohms, ground- temperature recorders
UM: °F, °C
F: intermittent - snow season
Soil Profile - Unsaturated Zone
I: thermogravimetric, electrical resistance blocks, neutron meters, network or plot studies
UM: ins, % moisture
F: intermittent - non-winter months (daily, weekly or monthly surveys)
Recharge - Percolation
(saturated flow)
saturated hydraulic conductivity and total potential head
field studies

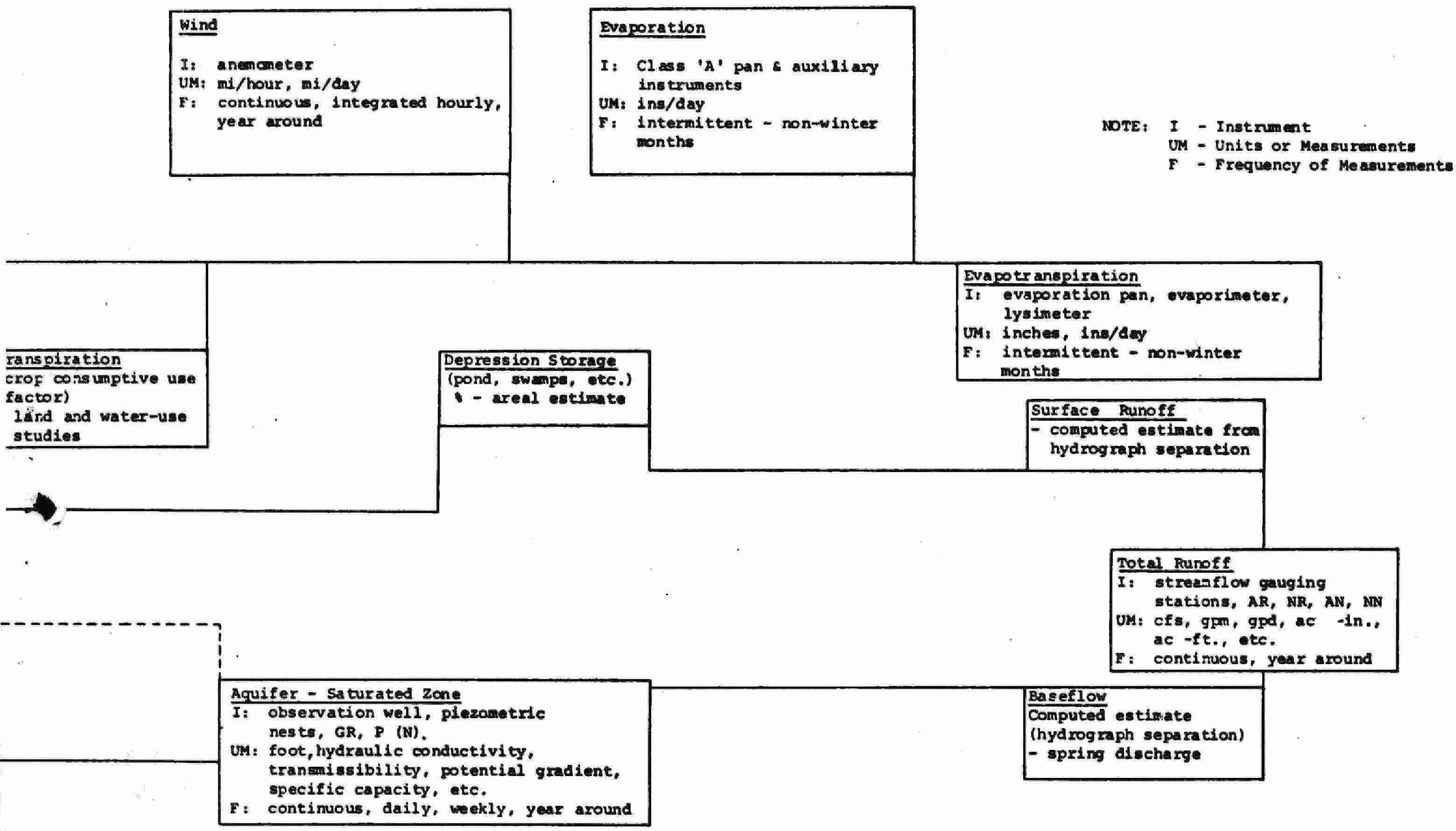


Figure 2: HYDROLOGIC MODEL: A Schematization for the Superposition of Basin Instrumentation upon the Functional and Interrelated Hydrologic Processes

APPENDIX III

HYDROLOGIC MODEL:

Component Models

In general, a component model refers to a mathematical formulation, involving operations with a data sequence of a single hydrologic process. This may be used for extending the data sequence or used to produce synthetic quantitative traces of the variables for use in simulation. These component models, schematized in Figure 3, are treated on the basis of lists of different methods and existing procedures that may be used for a model development. Quoted are some of the references relating to types of models.

The likely applicability of a type of model(s) to River Basin Research (RBR) present and projected investigations in the representative basins is also briefly discussed.

The cited references are given as examples of different types of investigations relating directly or indirectly to modelling. An attempt was made to identify the reviewed literatures and group them under the different component models. Identification was based on the type of hydrologic process and the choice of the method used in the modelling.

Precipitation Models

Method: Deterministic

- i) inter-station relationship (correlation and regression models) for use in data supplementation and extension.
- ii) storm transposition.

Probabilistic

- i) order statistics, e.g. conventional procedures for depth-area-duration analysis.
- ii) frequency analyses (probability of discrete events), e.g. storm intensity -frequency analysis and extreme values analysis.
- iii) random sequences, (stationary and non-stationary process), e.g. stochastic models for synthesis of hourly rainfall data, models of the types formulated by Grace and Eagleson (1967)*, Pattison (1965), Franz (1971), Raudkivi and Lawgun (1970), Hiemstra and Creese (1970).

* References appended in Bibliography.

Data Requirement

- historical data: daily, monthly and yearly summaries from the basin network stations; recording precipitation gauge data summaries; monthly, yearly, summaries from selected regional index precipitation stations.

Projected RBR Application

- each basin has 1 or 2 recording rain gauges and a network of standard rain gauges which provide the required data summaries.

- historical records of several long-term regional stations within each climatic region are available from monthly climatological station reports, published by the Atmospheric Environment Service, Canada.

- application in modelling may be attempted with data extensions, order statistics and sample computations based on frequency analysis and probability of discrete events. Some attempts may be made with stationary stochastic methods. This involves utilizing a time series of recording rain gauge data to formulate a stochastic model for use in simulating short-sequence rainfall data.

Snowmelt Models

Method: Deterministic

i) empirical equations - snowmelt synthesis with the use of general empirical snowmelt equations of the Corps of Engineers, U. S. Army (1960).

ii) melt indices - use of melt indices, e.g. degree-day index, or melt-plot studies, model by Watt and Hsu (1971).

iii) index plot and empirical equations - snowmelt simulation using a hybrid of index plot studies and empirical formulae, e. g. models formulated by Anderson and Crawford (1964), Amorocho and Espildora (1966), Crawford and Linsley (1966).

Data Requirement

- basic meteorological parameters (rainfall, temperature, radiation, vapour pressure, duration of sunshine, wind, convective heat transfer).

- areal extent of snow cover and snowpack parameters (depth, water equivalent, density, temperature, albedo of snow surface, permeability, etc.).

- streamflow records.

Projected RBR Application

- basic meteorological parameters are monitored continuously in each basin.

- areal extent of snow cover and snowpack parameters (depth, water equivalent, density, etc.), are determined seasonally in two basins.

- winter streamflows are monitored continuously.

- present application in modelling may be attempted with snowmelt hydrograph synthesis utilizing general melt equations and/or melt indices, e. g. models of the type formulated by Watt and Hsu (1970) which utilize a melt-index based on the degree-day concept, or a modified approach to the models used by Amorocho and Espildora (1966) which utilize empirical equations based on energy-melt concepts and index plot observations.

Soil Moisture Models

Method: Deterministic

i) *lumped-system as related to conceptual catchment storage; the use of soil moisture data, for specified soil types, in a budget-type equation to develop empirical relationships for use in estimating soil moisture regimes, e.g. models of the type used by Zahner (1967), Visser (1966), Baier (1969), Baier and Robertson (1965).
   - the use of depletion curves and accretion regressions from measured field data to develop empirical relationships for predicting moisture regimes, e. g. models of the types used by Carlson et al (1956), Stearn and Carlson (1960).

ii) lumped-system as related to infiltration; the use of soil moisture parameters in the modelling of infiltration process with methods such as those used by Overton (1964), Huggins and Monke (1968), Deboer and Johnson (1969), Skaggs et al (1969), Ligon, et al (1965).

Data Requirement

- soil types, land use and cropping practices and their areal distribution.

- hydrologic characteristics (moisture retention curves,

* 'lumped-system' - the spatial distributions of the input and output are ignored.

infiltration rates, hydraulic conductivity, etc.) of the major soil types.

- historical data of absolute soil moisture or changes in soil moisture for the study area, point measurements from a network of stations.

- meteorological variables (rainfall, temperature, radiation, humidity, evaporation, etc.).

Projected RBR Application

- soil moisture observations (absolute and changes in moisture from field studies) are being carried out in one sub-basin (BSW-Wilmot) and the initiation of a similar study is in progress for EMO.

- summaries of major soil types and land use and cropping practice in these basins are compiled.

- soil hydrologic characteristics to be determined by laboratory experiments on field samples.

- present application to modelling may be attempted with deterministic methods, such as the use of a water balance type equation to develop empirical relationships from field observations for use in estimating soil moisture regimes, e.g. method by Zahner (1967), Baier and Robertson (1965); the use of correlation relationships between soil moisture changes and meteorological variables to predict moisture regimes, e.g. method by Stearn and Carlson (1960); and the use of soil moisture parameters in infiltration models, e.g. method of Huggins and Monke (1968).

Evapotranspiration Models

Method: Deterministic

i) empirical relationships for potential evapotranspiration; the use of developed evaporation formulae which are based on the Energy-Budget and Mass-Transfer theories of evaporation such as the Penman or Thornthwaite formulae and method by Gay (1970); the use of adjusted Class-A pan data with other meteorological variables to develop correlation or regression relationships for use in predicting potential evaporation regimes, such as done by Mukammal and Bruce (1960), Christiansen (1966), Morton (1971), Harmon (1966).

ii) empirical relationships for determining actual evapotranspiration; the use of a water balance type equation with measured field data to develop an empirical relationship for use in predicting the evapotranspiration regime, such as the method used by Bowman and King (1965); the use of a meteorological budgeting technique with meteorological and soil moisture data to develop empirical relationships for estimating daily evapotranspiration, e.g. method by Baier (1966); the use of pan evaporation and meteorological variables to develop relationships for estimating actual evapotranspiration such as summarized by Hargreaves (1960); the use of solar radiation and temperature to estimate evapotranspiration, e.g. method by Robb (1966).

Probabilistic

i) time-series model; the use of time-series analysis on historical sequences of estimated potential evapotranspiration to determine a stochastic model for data generation and simulation, Chow and Kareliotis (1970).

Data Requirement

- historical data: hourly, daily, monthly or yearly summaries of meteorological data (radiation, temperature, humidity, wind speed, duration of sunshine, Class-A pan data, etc.).

Projected RBR Application

- the basic meteorological variables including Class-A pan evaporation data are monitored in each basin.
- application to modelling may be attempted with computations based on available empirical formulae or by trial computation with formulations through correlation and regression analysis, e. g. the application of a modified Penman's or Thornthwaite's equation and the development of regression relationships between Class-A pan evaporation and meteorological variables for use in data supplementing or data extension, or the use of a budget equation with measured meteorological and soil moisture data to develop relationships for use in estimating actual evapotranspiration.

Surface Runoff Models

Method: Deterministic

i) linear time-invariant; the use of a distributed

linear method for the synthesis of runoff hydrographs from given rainfall inputs, such as the Unit Hydrograph Method, as applied by Eagleson (1962), Mitchell (1967), Gray (1961), Viessman (1968), Overton (1967), Dooge (1959); Eagleson et al (1965); or the use of other routing methods such as the rational method and the summing of hydrographs from a number of sub-areas within a basin.

- the use of the physiographic parameters of the basin and surface runoff characteristics to develop regression equations for use in simulation, e. g. as developed by Narayana and Riley (1971), Schulz et al (1971), Taylor and Schwarz (1952), Larson (1965).
- the use of a hydraulic model of the catchment to simulate runoff, e.g. based on Kenematic wave theory as applied by Wooding (1965, 1966).

ii) non-linear time-invariant; the use of a distributed non-linear method to synthetise runoff hydrographs, e.g. IUH as applied by Singh (1964).

Probabilistic

i) frequency analyses; the use of peak flow data for annual or partial duration series to develop frequency curves and statistics for use in flood flow predictions, e. g. as applied by Snyder (1958).

- the use of the statistical parameters of flood series and rainfall extremes to develop regression relationships for use in simulation, e. g. as applied by Reich (1970), Shane and Gaver (1970).

ii) random sequences (stationary and non-stationary processes); the use of the stochastic property of flood flow series to develop a model for use in simulation, e.g. as applied by Todorovic and Zelenhasic (1970), Shane and Lynn (1964); the application of a stochastic model to storm runoff and rainfall data to formulate relationships for use in generating sequential data, after Chow and Ramasseshan (1965).

Data Requirement

- historical data: streamflow (mean daily and peak flows); recording precipitation summaries (amount, intensity, duration).

Projected RBR Application

- the use of deterministic and probabilistic methods - re synthesis of surface runoff hydrograph, with the use of unit hydrograph or instantaneous unit hydrograph techniques; re development of relationships between runoff hydrograph parameters and basin physiographic parameters; re development of frequency curves and parameter relationships for flood flow series; re development of regression relationships between flood flow and rainfall extreme series, etc.

Ground-Water (Baseflow) Models

Method: Deterministic

i) lumped-system; to consider the relationship between total quantity of precipitation and its direct runoff component, for use in estimating ground-water flow and rainfall loss relative to the infiltration capacity and soil moisture as applied by Kadoya (1967), Meyboom (1961).

ii) *distributed-system; to consider the theory of flow problems re models based on the analytical and numerical solution of the flow equation with given boundary conditions for specified problems, e. g. for a simplified, two-dimensional flow problem as applied by Toth (1962, 1963) and for multi-layered, two-dimensional flow problem as applied by Freeze and Witherspoon (1967); to consider heterogeneity of basin models by determining the statistical variability of input data (conductivity, specific yield, water-level elevation, spatial dimension of aquifer, etc.) e. g. solution of the flow equation with variable coefficients as applied by McMillan (1966), Shahbazi and Todd (1967), Kiraly (1971).

Probabilistic

i) correlation; to develop statistical relationships between baseflow data (determined by hydrograph separation techniques) and drainage basin parameters or meteorological parameters, e. g. relationship between drainage density and baseflow as applied by Trainer (1969), between baseflow and basin parameters as applied by Furness and Busby (1969), between ground-water chemistry and baseflow as applied by

* 'distributed-system' - the spatial distribution of the input and output is considered.

Pinder and Jones (1969); relationships of quantitative geomorphology to baseflow as applied by Farvolden (1963); relationship of recharge to ground water from storm inputs to increment in baseflow as applied by Trainer (1969).

Data Requirement

- surficial and subsurface geology.
- summaries of water-table fluctuations, spatial dimension of aquifers, chemical properties of ground water, pumping tests, etc.
- aquifer characteristics and their variability (specific yield, hydraulic conductivity, etc.)
- natural spring discharge measurements (where possible).
- low-flow data (streamflow hydrograph).

Projected RBR Application

- compilation of basic data (as above) is in progress.
- the use of parametric methods such as the lumped-system to relate indices of gross precipitation inputs, direct runoff components and corresponding antecedent moisture conditions.
- the use of simplified one or two-dimensional flow problem models.
- the use of correlation relationships between baseflow components and drainage basin or meteorological parameters.

Total Runoff Models

Method: Deterministic

i) linear time-invariant; the use of an antecedent-precipitation-index type of rainfall-runoff relationship and a retention index to simulate continuous streamflow hydrographs from rainfall inputs, e.g. as applied by Sittner et al (1969).

Probabilistic

i) regression and correlation; the use of multiple regression techniques to develop relationships between streamflow data at inter-related stations; to develop relationships between streamflow parameters and basin physiographic parameters; to develop relationships between the original variables or statistical parameters of rainfall and streamflow series, as applied by Beard (1965), Benson and Matalas (1967), Caffey (1965).

ii) auto-correlation; the use of stochastic models (Markov Models) on historical streamflow data to develop relationships for use in generating synthetic data; the use of a 2nd-order Markov model, applied to standardized variates (assumed log-Pearson Type III distribution), e. g. method by Beard (1967); the use of Markov model for low-flow analysis, e. g. method by Fiering (1964); the use of a 1st-order Markov model and regression analysis on multiple-station flow data to develop a simulator for generating daily flows, after Payne and Newman (1969).

iii) other time-series analyses; the use of time series analyses on historical streamflow data to determine the inherent stochastic model for use in data generating; the autocorrelation and spectral analysis of streamflow series, after Quimpo (1967), Roesner and Yevdjevich (1966), Svandize (1967).

Data Requirement

- historical data: streamflow (mean daily, monthly and yearly summaries) for both base and secondary gauging stations; precipitation summaries.

Projected RBR Application

- compilation of streamflow data for each basin gauging network is in progress.
- application of deterministic and probabilistic methods - re synthesis of total runoff hydrographs, using a developed relationship between antecedent-precipitation-index, retention-storage-index and runoff, or using a multi-station regression relationship, or using a regression between streamflow and basin parameters and/or meteorological parameters.
- application of probabilistic methods - re use of simpler Markov models for data generation (generating models based on mean, standard deviation and serial correlation of a flow sequence).

Transformation System (Catchment) Models

Method: Deterministic

i) lumped-system; to consider the catchment as a linear system, governed by a differential equation, the integration of which provides the convolution equation for the linear transformation of an input (index of precipitation) to an output, as applied by Amorocho and Orlob (1961), O'Connell and Nash (1970).

ii) distributed-system; to consider the catchment to be composed of an infinite array of lumped, independent linear subsystems with each subsystem being governed by a linear differential equation, the summation and integration of which leads to the convolution relationship for transforming inputs to outputs, as applied by Eagleson (1967), Wooding (1965, 1966), Brakensiek and Onstad (1968), Huggins and Monke (1970), Foster, et al (1968).

iii) linear reservoir; to consider the catchment as a single reservoir or a cascade of n-linear reservoirs, in each of which the storage is linearly related to the outflow, e. g. use of the storage equation and the hydrologic continuity equation to derive the differential equation that governs the linear reservoir, as applied by Nash (1957), Sarma et al (1969), Overton (1967), O'Connell, et al (1970).

iv) linear channel and linear reservoir; to consider the catchment to consist of a series of linear channels and linear reservoirs having a combined linear translation effect, using a time-area-concentration diagram as applied by Dooge (1967).

v) non-linear channel and reservoir; to consider the catchment storage to be distributed and non-linear by dividing the catchment into sub-areas, considering their individual inputs and routing the excess from each sub-area through different amounts of storage, as applied by Laurenson (1964), Deboer and Johnson (1969); to consider the operation of the catchment by a functional series (the generalization of the U.H. concept to that of a non-linear response function) as treated by Amorocho and Orlob (1961), Machmeier and Larson (1967), Overton (1967), Prasad (1971).

Probabilistic

i) the use of a linear regression relationship between inputs and outputs of the system, as applied by Diskin (1970).

ii) to consider the catchment as a stochastic hydrologic system; formulate a system model on the basis of conservation of mass regarding the components (precipitation, runoff, storage and evapotranspiration) as individual stochastic processes, as applied by Chow and Kareliotis (1970).

Data Requirement

- physiographic parameters of the drainage basin (area, drainage density, slope, main stream length, etc.).
- historical data or hydrologic parameters (precipitation, runoff, etc.)

RBR Projected Application

- the use of the lumped-systems re application of a convolution integral to transform lumped inputs to outputs.
- the use of simpler distributed system re application of the convolution integral to sub-systems.
- the use of a single or double linear reservoir storage re application of the storage and hydrologic continuity equations to derive the differential equation that governs the input-output relationship.
- the use of linear channel translation and linear reservoir storage re application of a time-area-concentration relationship for the transformation of inputs to output.
- the use of a linear regression relationship between precipitation and runoff.

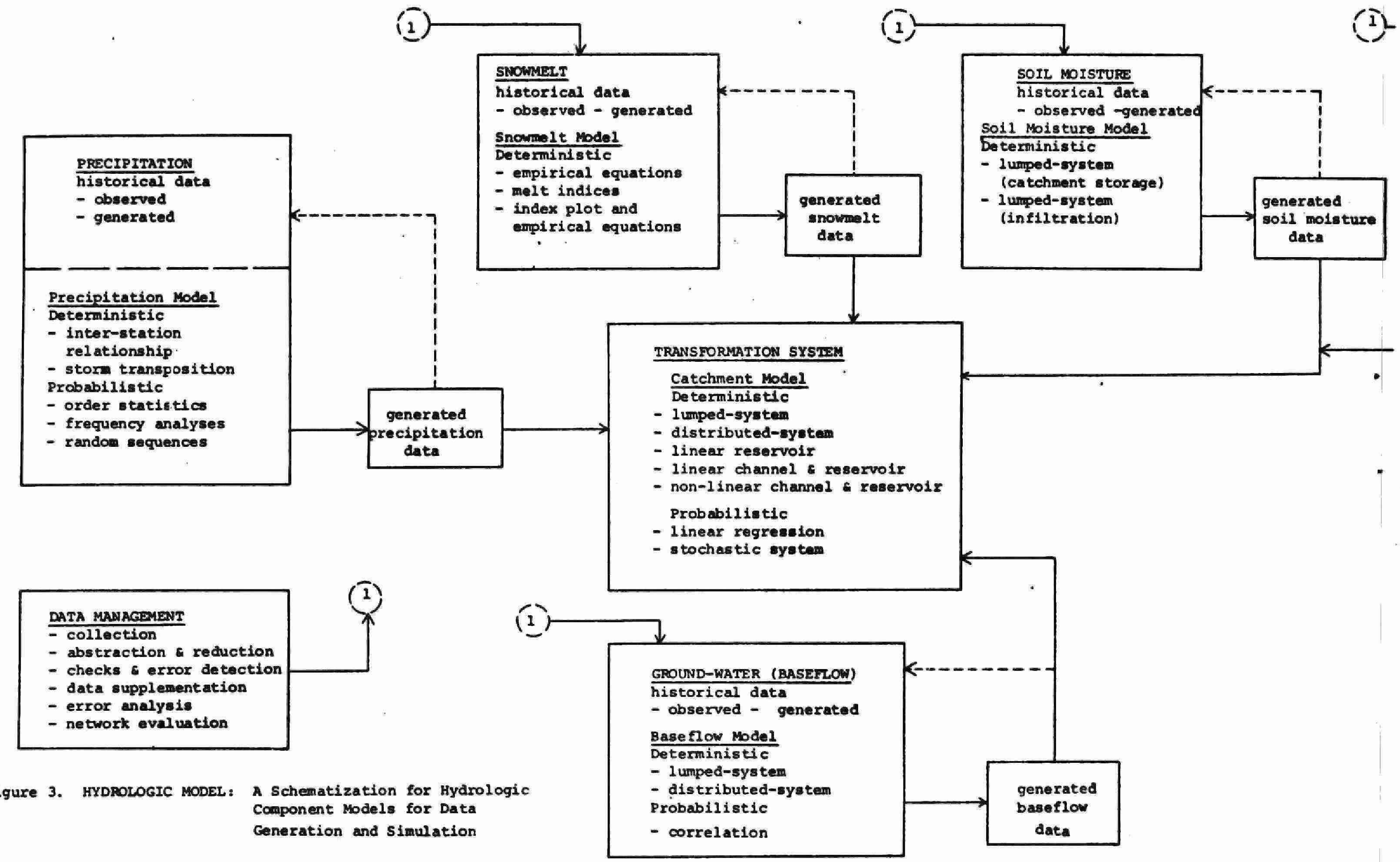
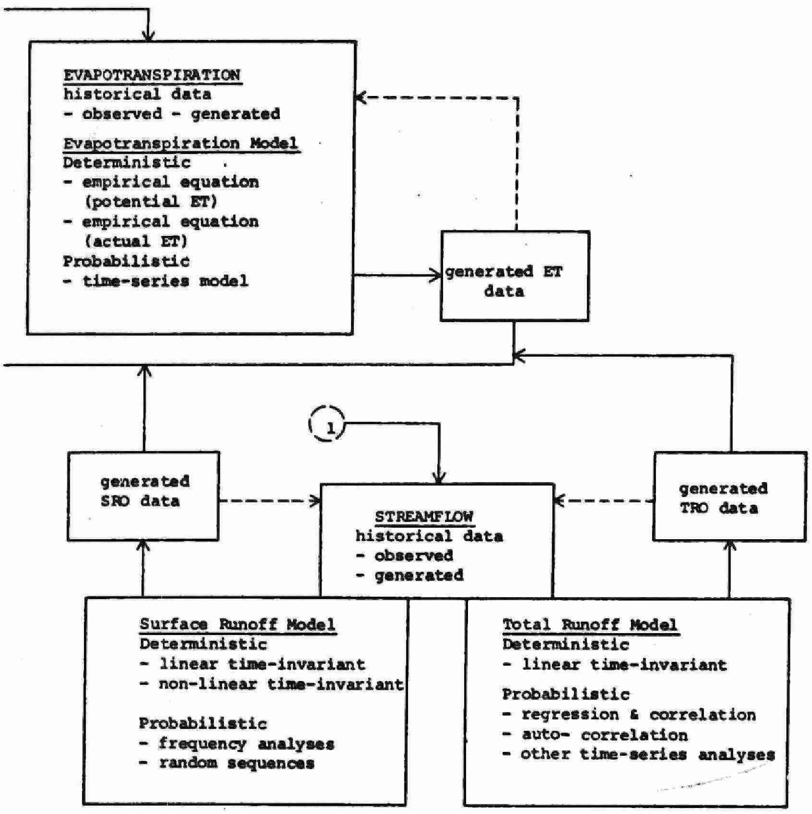


Figure 3. HYDROLOGIC MODEL: A Schematization for Hydrologic Component Models for Data Generation and Simulation


EVAPOTRANSPIRATION
historical data
- observed - generated
Evapotranspiration Model
Deterministic
- empirical equation (potential ET)
- empirical equation (actual ET)
Probabilistic
- time-series model
generated ET data
1
generated SRO data
STREAMFLOW
historical data
- observed
- generated
generated TRO data
Surface Runoff Model
Deterministic
- linear time-invariant
- non-linear time-invariant
Probabilistic
- frequency analyses
- random sequences
Total Runoff Model
Deterministic
- linear time-invariant
Probabilistic
- regression & correlation
- auto- correlation
- other time-series analyses

APPENDIX IV

HYDROLOGIC MODEL:

An Integrated Hydrologic System Model

Figure 4 shows a schematization for an integrated hydrologic system model.

Precipitation

Precipitation, P, as rain and/or snow (snowmelt) is the initializing input to the system. The initial amount is intercepted to some degree by the vegetal canopy.

Interception Storage

The intercepted precipitation is held by the vegetal canopy as Interception Storage, IS. This IS is a function of the amount of P, the duration of the precipitation, t_r, the evaporation rate, E_a, at the intercepting surface, the interception storage capacity, ISC, of the intercepting area and the ratio of the evaporating surfaces to the total horizonally projected canopy surface area, A. An explicit function relating these parameters is required for use in determining IS from the gross P.

Surface Storage

The excess precipitation goes to satisfy the Surface Storage, SS, requirement. The Surface Storage is composed of three conjunctional functions, namely the Depression Storage, DS, the Detention Storage, D, and Infiltration, I. Some explicit function is required to distribute the excess precipitation to the requirements of DS, D and I. Generally I reacts simultaneously with DS and D to the precipitation input, but DS is normally satisfied or partially satisfied before the initiation of D.

Depression Storage

The Depression Storage, DS, is a function of the depression storage capacity, DSC, of the drainage area, the amount of precipitation excess, P_e, the infiltration characteristics of the soil, ic, and the ratio of the depressional storage area to the total drainage area, B.

Detention Storage

The Detention Storage, D, is a momentary storage which is a function of the overland flow length, L, the infiltration characteristics, ic, and the overland flow rate, q. The flow rate q, in turn, is a function of the overland flow length, L,

the slope, S, and the flow characteristics (Manning's roughness coefficient, n) of the overland flow path and the rate of precipitation input, i. Whenever the input rate, i, is greater than the rate of infiltration, overland flow, OLF, is initiated and is routed out of Detention Storage D in terms of q.

The OLF out from D is routed to the streamflow according to some method of linear or non-linear channel storage and flow translation to produce the direct Surface Runoff, SRO, component of the Total Runoff, TRO, measured at the basin outlet.

Infiltration

The Infiltration rate, I, is a function of the soil moisture, SM, the amount of excess precipitation, P_e, the rate of precipitation input, i, the initial infiltration rate, I_o, and the infiltration capacity, I_c, of the soil. Infiltration proceeds at a decreasing rate with time; the initial rate is dependent on the antecedent soil moisture condition and continues at a rate subject to I_c, until the liquid amounts in DS and D become limiting. Several empirical infiltration formulae have been developed by many investigators (Horton, Holtan, Huggins and Monke, Phillip, et al). A few of these empirical formulae have been suitably applied to describe the infiltration process in source accounting type hydrologic models. The infiltration rate function may be examined by the standard flow equation which relates the inflow rate, V_o, to the hydraulic conductivity, K, and the diffusivity, ($D = K/ \frac{d\,(SM)}{d\psi}$,), of the soil and to the differential change in soil moisture with depth, $\frac{\partial\,(SM)}{\partial\, y}$, relative to the soil surface. An empirical determination of K and D and a numerical approximation technique for solution, are required for incorporation of the infiltration rate function into a working model.

Aeration Zone Storage

Infiltrated water moves through the soil profile in accordance with known physics of flow through porous media thereby satisfying the moisture requirement of the Aeration Zone Storage, AZS. The soil moisture, SM, is a function of the flow characteristics of the soil, i.e. unsaturated hydraulic conductivity, $K_{unsat.}$, capillary potential, ψ, gravity potential, y and total porosity, T_p, of the medium. Flow of water in the unsaturated zone can be described by the expanded partial differential Darcy flow equation, which is the same standard

flow equation for infiltration above, but written in the more classical form, $\frac{\partial (SM)}{\partial t} = K_{unsat.} (\frac{\partial \psi}{\partial y} + 1)$, relating the rate of change of moisture content with the hydraulic potential.

Interflow Zone Storage

Infiltrated water, drained by gravity from the Aeration Zone Storage, AZS, percolates to the Interflow Zone Storage, IZS. Saturated flow is characteristic of the IZS zone. This zone is in fact a transient saturated zone or a saturated zone created by a less permeable layer below the more permeable soil profile, thereby forming a 'perched water table'. The physics of saturated flow can be used to describe the seepage to be routed out of this IZS, as interflow, INFL, which is subsequently routed into the streamflow as part contribution to Total Runoff, TRO.

Saturated Zone Storage

Drainage by percolation from the IZS goes to recharge the Saturated Zone Storage, SZS. Moisture flow in this zone is characteristically saturated flow. The outflow q, is dependent on the amount Q_o in storage and the total hydraulic potential, H; the outflow rate being regulated by the saturated hydraulic conductivity, $K_{sat.}$. For saturated flow, SM and $K_{sat.}$ are constants; and $\partial(SM)/\partial t = o$. With these known conditions the differential flow equation may be solved for unconfined steady-state flow in an isotropic porous medium resulting with the Laplace's equation $\nabla(K \nabla H) = 0$. For a given drainage problem with defined boundary conditions, the differential flow equation for the problem may be expressed explicitly. With the use of numerical approximation techniques, the explicit flow equation may be solved approximately and so facilitates the routing of a base-flow component BFL, out of SZS, into streamflow as another part contribution to TRO.

The sum of INFL and BFL constitute the subsurface runoff, SSRO, component to TRO.

Total Runoff

The Total Runoff, TRO, may be routed through the channel reach by a linear (or non-linear) storage equation utilizing the law of continuity in the basic routing procedure. This TRO may be reproduced at the basin outlet as the streamflow hydrograph.

Evapotranspiration

Actual Evapotranspiration, ET, is directly proportional to the amount of moisture available in the various storages, SSM, to the amount of available energy fluxes in terms of radiation, R, and temperature, T, to a crop use factor C_f and wind speed u, and is indirectly proportional to the relative humidity, H, of the environment.

Evaporation takes place, from the IS and SS at the potential rate until the free water available in the sources is used up. Evaporation also takes place from AZS, IZS and/or SZS, at a rate which is proportional to the rate at which the water is supplied to the soil surface through capillarity.

Transpiration, by plants, from the AZS, IZS and/or SZS is controlled by the amount of moisture available to the plant. In the case of the AZS, this availability of moisture is limited to the range between that of field capacity and wilting point.

An explicit function (not shown diagrammatically) such as one relating ET to the potential evapotranspiration rate and soil moisture, SM, in the AZS, to crop-use, is required for incorporation into the model to account for ET loss from the basin.

Working Model

The development of a working model based on, or modified from, Figure 4 requires that a choice be made of an existing explicit function for each component of the model. Explicit functional relationships may also be developed independently through empiricism based on observations and plot studies. A linkage or step relationship is also required for the computational sequences between the different component schemes.

LIST OF SYMBOLS IN MODEL

IS = INTERCEPTION STORAGE - in.

P = gross precipitation - in.
t_r = duration of storm - in/hr.
E_a = rate of evaporation from the intercepting surface - in/hr.
A = ratio of evaporating surface to projectional area - sq.mi.
ISC = storage capacity of the intercepting surface areas - in.

SS = SURFACE STORAGE - in.

DS = Depression Storage - in.

DSC = Depression Storage Capacity - in.
ic - refers to the infiltration characteristic of the soils
P_e = excess precipitation (P - IS) - in.
B = ratio of depressional storage area to total drainage area.

D = Detention (overland flow) Storage - in.

L = length of the overland flow reach - ft.
ic = infiltration characteristic of the soils
q = rate of overland flow per unit area - in/hr.
S = slope of the overland flow surface - ft/ft.
n = a Manning's roughness factor for overland flow
i = the inflow (precipitation) rate - in/hr.
OLF = overland flow - in.

I = Infiltration Rate - in/hr.

SM = soil moisture -in.
I_o = initial infiltration rate - in/hr.
I_c = infiltration capacity - in/hr.
P_e = amount of precipitation excess - in.
i = inflow (precipitation) rate - in/hr.

- Flow Equation -

V_o = inflow rate - in/hr.
K = hydraulic conductivity - in/hr.
D = $K/\frac{d\ SM}{d\ \psi}$ is the soil diffusivity - in/hr., where
$\frac{d\ (SM)}{d\ \psi}$ = moisture capacity i.e. the differential change in soil moisture with a change in capillary potential

$\frac{\partial (SM)}{\partial y}$ = partial differential change in soil moisture with soil depth relative to the surface (when moisture supply is not a limiting condition)

N.B. I_c = saturated hydraulic conductivity $K_{sat.}$

AZS = AERATION ZONE STORAGE (UNSATURATED SOIL PROFILE)

SM = soil moisture - in. per unit depth
ψ = capillary tension - in.
y = gravity potential - in.
T_p = total porosity of given soil profile
$K_{unsat.}$ = unsaturated hydraulic conductivity.

- Flow Equation -

$\frac{\partial (SM)}{\partial t}$ = partial differential change in soil moisture with time, t

$\frac{\partial \psi}{\partial y}$ = partial differential change in soil moisture tension

SM = f (ψ); relates soil moisture as a function of the capillary tension ψ and

$K_{unsat.}$ = f (ψ,SM); relates the unsaturated conductivity as a function of the capillary tension and soil moisture; these are secondary relationships required to be developed as aid in the numerical solution of the partial differential flow equation.

IZS = INTERFLOW (INTERMEDIATE) ZONE STORAGE

q = the outflow rate from the IZS - in/hr., cfs
Q_o = relates to the volume of interflow in storage - cu.ft.
H = total hydraulic potential.

- Flow Equation -

$\nabla(K\nabla H)$ = the Laplace's equation for unconfined steady-state flow in an isotropic porous medium
$K_{sat.}$ = saturated hydraulic conductivity.

SZS = SATURATED ZONE STORAGE

q = outflow rate from SZS - in/hr., cfs
Q_o = volume in storage in baseflow - in.
H = total hydraulic potential ($P/\gamma + Z$), where P is the pressure potential, γ the density of water and Z, gravity potential.

SRO = SURFACE RUNOFF ROUTED INTO STREAMFLOW

q_t = surface discharge (output) from the basin at time t, in cfs

X_a = successive input volume up to time, t

h_{t-a} = a time-area distribution parameter (distribution graph) for the successive input volumes - e. g. I.U.H. technique; $\sum_{a=o}^{t}$ = summation over time t, for increments, a.

INFL = INTERFLOW ROUTED OUT OF IZS INTO STREAMFLOW

q_t = interflow rate - cfs at time, t

$\hat{K}$ = an interflow recession constant

q_o = initial interflow rate (N. B. - routing relationship assumed to be similar to that of BFL).

BFL = BASEFLOW ROUTED OUT OF SZS INTO STREAMFLOW

q_t = baseflow rate - cfs at time, t

K = a baseflow recession constant - (N. B. - the routing function may require adjustments to account for variable component of ground-water recession)

q_o = initial baseflow rate.

TRO = TOTAL OUTFLOW AT BASIN OUTLET

- Route via linear channel storage and flow translation

I = input

Q = output

K = storage coefficient

$\frac{dQ}{dt}$ = time rate of change in Q.

ET = ACTUAL EVAPOTRANSPIRATION

SSM = supply of moisture (water) available for evapotranspiration - amount available in IS, SS, IZS and AZS - in.

R = radiation - langley.

T = temperature - ^{o}F, or ^{o}C

u = wind- m.p.h.

H = relative humidity, H

C_f = a crop (vegetation) -use factor.

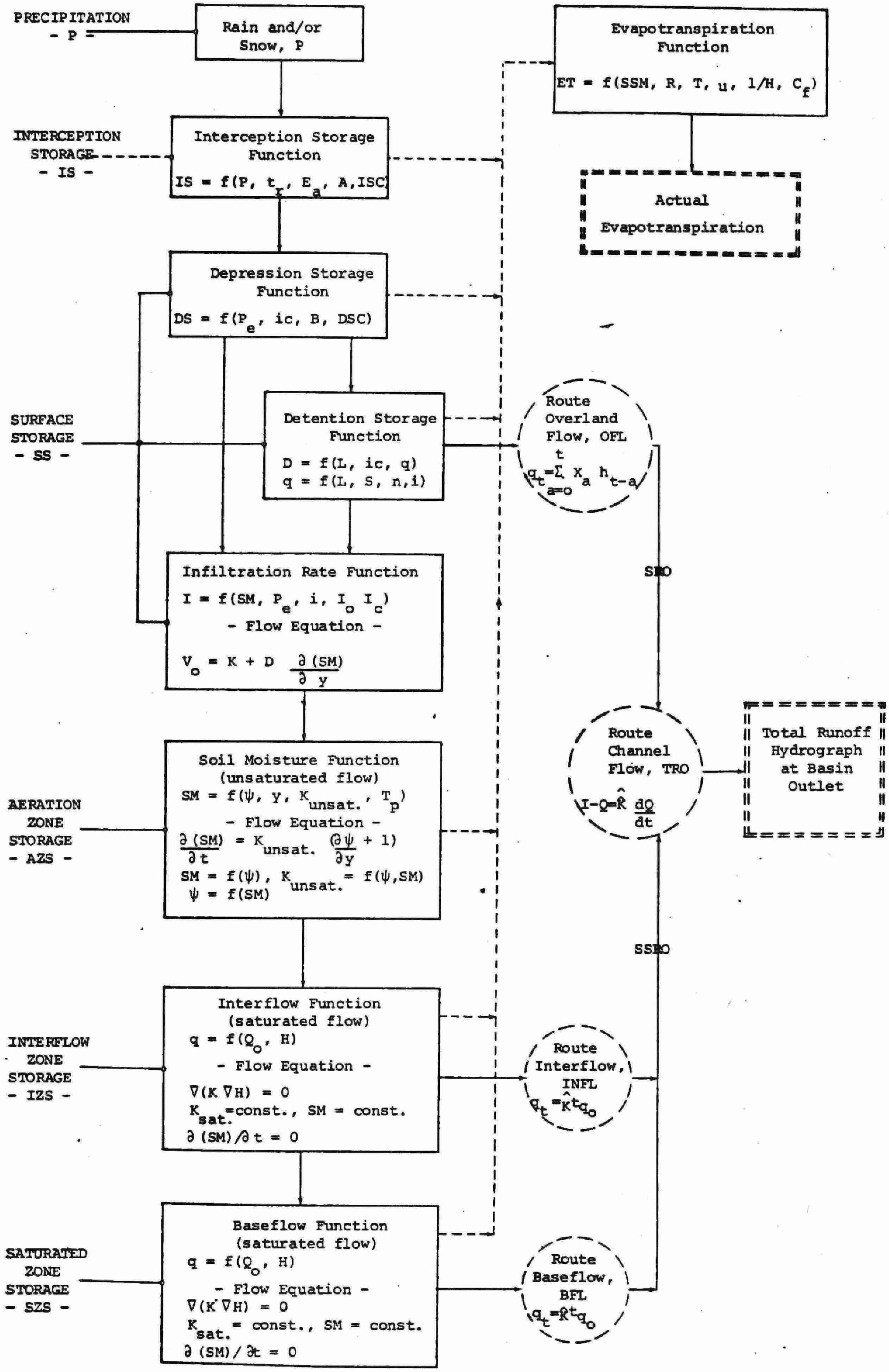


Figure 4. HYDROLOGIC MODEL: A Schematization for an Integrated (Comprehensive) Hydrologic System Model

APPENDIX V

HYDROLOGIC MODEL: A Specific Model Approach

A Simple Regression Model

The following gives an outline for the definition of a parametric, linear regression model, according to the conceptual model scheme of **Figure** 5a.

The basic relationship for a simple linear regression, rainfall-runoff model may be expressed as:

$$R = a + bP \qquad \text{... (1a)}$$

with $$b = \sum_{i=1}^{n} (R_i - \bar{R})(P_i - \bar{P}) / \sum_{i=1}^{n} (P_i - \bar{P})^2 \qquad \text{... (1b)}$$

and $$a = \bar{R} - b\bar{P}$$

where
R = runoff
P = precipitation
a = least-square regression constant (usually negative)
b = least-square regression coefficient (usually < 1.0)
$i = 1, 2, ...n$

Operation in the Whole System: One-Element Model, EO - Figure 5a

i) Relationship in terms of runoff, R:

If $P \leq C_o$
$$R = o \qquad \text{... (2)}$$

If $P > C_o$
$$R = b_o (P - C_o)$$
$$R = b_o P + a_o \qquad \text{... (3)}$$

with
$$a_o = -b_o C_o = \text{constant.}$$

where, C_o is a numerical parameter in EO, related to the surface and subsurface storage or retention characteristic of the drainage basin,
b_o is regression coefficient, an operator needed to convert P (input to the system) to R (output from the system) and may be

related to the runoff characteristics of the basin; a_o is a regression constant, or a parameter related to the moisture deficit and retention of the soils (a minimum moisture requirement of the basin to be satisfied before the initiation of additional runoff by a given input P).

ii) Relationship in terms of basin loss, L:

If $P \leq C_o$

$$L = P \qquad \ldots (4)$$

If $P > C_o$

$$L = P - R$$

$$L = P - b_o (P - C_o)$$

$$L = b'_o P + a'_o \qquad \ldots (5)$$

with $b'_o = (1 - b_o)$ and

$a'_o = b_o C_o$ = constant.

b'_o is a regression coefficient or a parameter needed to convert portion of the P (retained or stored in the system) to loss L (output from the system) and may be related to the transpiration and evaporation characteristics of the vegetation and soil, respectively, in the basin,

a'_o, is a regression constant, or a parameter related to a minimum moisture loss from the system when the moisture supply is not limiting.

<u>Operation in the Whole System: Three-Element Model, E1, E2 and E3 - Figure 5a</u>

i) In Element E1:

If $P \leq C_1$

$$R_1 = o \qquad \ldots (6a)$$

$$L_1 = P \qquad \ldots (6b)$$

If $P > C_1$

$$R_1 = P - C_1 \qquad \ldots (7a)$$

$$L_1 = C_1 \qquad \ldots (7b)$$

where, C_1 is a numerical parameter in Element, E1, related to the initial surface storage or retention characteristic of the system,

L_1 is the potential loss from Element, E1, with a maximum capacity C_1 and

R_1 is the output from E1 which is a virtual input to Element, E2.

Element, E1, may represent the surface storage characteristics of the basin (interception by vegetation is neglected).

ii) In Element E2:

$$R = b_1 R_1 \qquad \text{... (8a)}$$

$$L_2 = (1 - b_1)\ R_1 \qquad \text{... (8b)}$$

substituting equation 7a into equation 8a and 8b:

$$R = b_1\ (P - C_1)$$

$$R = b_1\ P + a_1 \qquad \text{... (8c)}$$

with

$$a_1 = -b_1 C_1 = \text{constant.}$$

$$L_2 = (1 - b_1)\ (P - C_1)$$

$$L_2 = (1 - b_1)\ P + a'_1$$

$$L_2 = b'_1\ P + a'_1 \qquad \text{... (8d)}$$

with

$$b'_1 = (1 - b_1)$$

$$a'_1 = -b'_1\ C_1 = \text{constant.}$$

where, b_1 and b'_1 are factors, (regression coefficients) needed for the conversion of input R_1 into runoff, R, or loss, L_2, respectively.

a_1 and a'_1 are regression constants or parameters which may be related to the moisture deficit and moisture retention that has to be satisfied, before the initiation of runoff or loss from the system.

Element, E2, may represent subsurface storage or retention characteristics of the basin.

iii) In Element E3:

$$L = L_1 + L_2 \qquad \dots (9)$$

where, L is the total potential loss from the drainage basin, i. e. that portion of the precipitation input that is not accounted for by the measured runoff.

E3 is a 'dummy' element introduced to provide for the summation of the potential losses from E1 and E2.

Application of the Simple Regression Model

Basic criteria:

a) - drainage basin; select a basin that exhibits a recurrent storage condition at the onset of each major seasonal change, e. g. onset of major spring runoff when the basin storage is at a maximum; or select a basin with runoff sequences that may be regarded as having negligible contribution from adjacent basins.

b) - time interval; select a time interval for the analysis that indicates a negligible lag or autocorrelation effect in the respective time series of precipitation or runoff data, e.g. monthly, seasonal or annual series.

Data Requirement

- concurrent series of precipitation and runoff(monthly or annual series).

If monthly series are to be used, it is suggested that a normalization procedure be performed on the data prior to the regression analysis, e.g. use the logarithms of the original data assuming that the variates are log-normally distributed.

Parameter Evaluation

Gross estimates of C_o or C_1 may be assigned from knowledge of the major soil types in the basin and their areal distribution and moisture characteristics, the surficial geological characteristics, the recharge and discharge areas and the major aquifer storage characteristics.

The constants and coefficients in the regression model equation (1a) may be determined by operating with the concurrent series of P and R in a standard least-square regression analysis

subject to satisfying a threshold precipitation value:

$$R = a + bP, \text{ for } P > P_o$$

$$R = o, \text{ for } P \leq P_o$$

where, P_o is the threshold value (e.g. infiltration index) required to be satisfied before the initiation of runoff.

Expanded (Multiple) Regression Model

Consider the multiple regression:

$$y = \sum_{k=1}^{n} X_k + a$$

where, y is the dependent variable (runoff)
X_k are the independent variables (precipitation, evapotranspiration, etc.); K = 1, 2...n independent variables and
a is the regression constant.

If the basin water balance or conceptual storage equation is used as a physical base,

$$R = f(P, L, S)$$

with $$L = f_1 (E, G) \text{ and}$$

$$S = f_2 (S_a, S_b)$$

where, R is the runoff and is a function of the precipitation, P, the basin loss, L, and the basin storage, S; in turn, L is a function of the evapotranspiration, E, and the loss to ground-water flow systems, G; and S is a function of the soil moisture storage, S_a, and the ground-water storage, S_b.

Operation in the Whole System: Expanded Three-Element (Multiple-Element) Model - Figure 5b

i) Operation in Elements E1, E2 and E3

It should be noted that the operations in E1, E2 and E3 are as per previous development for the Three-Element Model, with the exception that the output R_2 from E2 represent a virtual surface runoff. This is further augmented in E5 for baseflow contribution to give output R from the system:

$$R_2 = b_1 R_1 \qquad \ldots (10)$$

where, the coefficient b_1 usually differs in value from the coefficient in equation (8a) of the Three-Element model. Also, the operations in E4a and E4b represent sub-operations extruded from E1 and E2.

ii) Operation in Element E4

By definition, S = L, that is, input to storage is equivalent to the potential losses, accounting for evapotranspiration, change in storages and loss to regional flow system.

Let C_2 be a numerical parameter in Element E4 related to the total water-holding capacity of the soil profile, i.e. total porosity, and assuming that the surface supply is an instantaneous input to the soil profile.

If $S \leq C_2$

$$S_a = S \qquad \ldots (11a)$$

$$S_b = o \qquad \ldots (11b)$$

If $S > C_2$

$$S_a = S_a \text{ (capacity)} \qquad \ldots (11c)$$

$$S_b = S - S_a \text{ (capacity)}$$

where, S_a is the increase to available soil moisture in the soil profile (unsaturated zone) and
S_b is the percolation (drainage) to the water table (saturated zone).

iii) Operation in Sub-Element, E4a

By definition S_a (capacity) = C_3, where, C_3 is a numerical parameter in E4a related to the moisture capacity of the unsaturated zone, after drainage by gravity (i.e. field capacity).

$$S_a \leq C_3$$

$$E = b_2 S_a \qquad \ldots (12a)$$

$$\Delta S_a = (1 - b_2)\, S_a \qquad \ldots (12b)$$

where, E is evapotranspiration (actual)
b_2 is a parameter or regression coefficient needed to

convert a portion of the available soil moisture to actual E,

$(1-b_2)$ is related to the soil moisture-retention characteristics and

ΔS_a is the incremental change in soil moisture storage.

iv) Operation in Sub-Element, E4b

Let C_4 be a numerical parameter in E4b related to a base storage condition of the local ground-water flow system, i.e. the aquifer storage condition necessary to sustain a minimum baseflow (assuming that fixed proportions of the recorded precipitation are transformed simultaneously to baseflow and changes in storage).

If $S_b << C_4$

$$G = C_4 \quad \text{... (13a)}$$

$$G_b = b_3 G \quad \text{... (13b)}$$

$$G_r = o \text{ (assumed)} \quad \text{... (13c)}$$

$$\Delta S_b = (1 - b_3)\ G \quad \text{... (13d)}$$

If $S_b \geq C_4$

$$G = S_b + C_4 \quad \text{... (14a)}$$

$$G_b = b_3 G$$

$$G_b = b_3 S_b + a_3 \quad \text{... (14b)}$$

with $a_3 = b_3 C_4 = \text{constant}$

$$G_r = o \text{ (assumed)}$$

and $\Delta S_b = (1 - b_3) G$

$$\Delta S_b = (1 - b_3)\ S_b + a'_3 \quad \text{... (14c)}$$

with $a'_3 = (1 - b_3)\ C_4 = \text{constant.}$

If $S_b >> C_4$

$$G = S_b + C_4$$

$$G_b = b_3 S_b + a_3$$

$$G_r = b'_3\ G$$

$$G_r = b'_3 S_b + a''_3 \quad \text{... (15a)}$$

with $a''_3 = b'_3 C_4$ = constant

and $\Delta S_b = (1 - b_3 - b'_3)\ G$

$$\Delta S_b = (1 - b_3 - b'_3)\ S_b + a'''_3 \qquad \text{... (15b)}$$

with $a'''_3 = (1 - b_3 - b'_3)\ C_4$ = constant,

where, G is the total potential outflow from the local ground-water flow system,

G_b is the local ground-water contribution as baseflow,

G_r is the loss from the local ground-water flow system to the regional flow system through deep percolation,

b_3 is the regression coefficient needed to convert a portion of the ground-water storage to a baseflow contribution and

$(1 - b_3)$ may be related to the aquifer storage characteristics.

a_3 is a regression constant and may be related to minimum baseflow contribution,

b'_3 is a regression coefficient needed to account for that portion of recharge lost, through deep percolation, to the regional flow system and

$(1 - b_3 - b'_3)$ may also be related to the aquifer storage characteristics,

a''_3 may be related to a minimum deep percolation loss where recharge to local ground-water flow is not limiting,

a'_3 and a'''_3 may also be related to the overall aquifer storage characteristics, and

ΔS_b is the incremental change in ground-water storage.

v) Operation in Element, E5

$$R = R_2 + G_b \qquad \text{... (16)}$$

where, R is the total runoff from the system. E5 is a 'dummy' element introduced to provide for the summation of the conceptual surface runoff and baseflow to produce the streamflow.

Application of the Multiple Regression Model

Consider the multiple regression model involving P, E and S as predictors of runoff, R:

$$R = a_o + b_1 P + b_2 E + b_3 S \qquad \text{... (16)}$$

where, a_o, b_1, P, b_2, E, b_3 and S are as previously defined.

Definition of the Model Parameters

Equation (16) can be written according to a regression model (Amorocho and Orlob, 1961) as equation (17):

$$R = b_1 P_1 + b_2 E_c + \sum_{j=1}^{m} a_j P_j + a_o \qquad \ldots (17)$$

where, R is the observed runoff,
P_1 is the recorded precipitation,
E_c is the computed estimate of evapotranspiration,
$\Sigma a_j P_j$ represents the storage term, S, in which P_j is concurrent and antecedent precipitation values ; $j = 1,2,\ldots,m$ period.
a_o, a_j, b_1, b_2, are regression constants and coefficients.

The input parameters P and E_c are determined with a certain amount of error in their estimates viz.,

a) Inflow - Index:

$$P_1 = b'_1 P \pm e_p \qquad \ldots (18)$$

where, P_1 is an estimate of the areal average precipitation,
P is the station(s) recorded amount,
b'_1 a station weight (coefficient) for areal distribution of P and
e_p is the standard error of the average.

b) Evapotranspiration - Estimate:

$$E_c = b'_2 E \pm e_c \qquad \ldots (19)$$

where, E_c is the areal average estimate of evapotranspiration,
E is the station(s) computed estimate,
b'_2 a station weight (coefficient) for areal distribution of E and e_c the standard error of estimate.

c) Storage - Index:

If it is assumed that fixed proportions of the total recorded precipitation are transformed into ground-water outflow, simultaneously producing changes in storage, then the storage index term of equation (17) may be interpreted as:

$$\Delta S_a + \Delta S_b + G_r = \Sigma a_j P_j + a_o \qquad \ldots (20a)$$

where, ΔS_a, ΔS_b are change in soil moisture and ground-water storage and G_r is deep percolation loss.

If G_r is assumed to be negligible, with an appropriate selection of the time interval, the storage index, S, may be estimated with presumably small error, from:

$$S = I_N - G_b \quad \text{... (20b)}$$

where, I_N is the net inflow at the soil surface and G_b the baseflow,

which may be determined from total runoff hydrographs by hydrograph separation techniques. Incidentally, the net inflow may be examined on the basis of:

$$I_N = \sum_{j=1}^{m} a_j P_j + a_o + G_b \quad \text{... (21)}$$

Model Simplification

The following statistical criteria are given for the simplification of the model relative to the selection of appropriate time periods for the analyses. At certain periods, some of the major parameters may tend to a constant due to recurring climatic conditions. For example, to examine the statistical degree of accuracy with which R can be estimated on the basis of a multiple regression model,

$$y = \sum_{k=1}^{n} X_k + a \quad \text{... (22a)}$$

(where, X_k are random independent variables),

usually the best choice of an end-point is when the variance of the observed values of a given variable is at a minimum, or when its values are approximately equal to the average value for the period of observation.

To examine this, consider the variance of the regressed estimate, y:

$$\text{Var } (y) = \sum_k \text{var } (X_k) + 2 \sum_{j,k} \text{Cov } (X_j X_k) \quad \text{... (22b)}$$

where, X_j and X_k are specified independent variables. Minimization of the error in y may be examined by the following relationships:

$$\frac{\partial \text{ Var } (y)}{\partial \text{ Var } (X_k)} = o \quad \text{... (23)}$$

$$\frac{\partial \text{ Var } (y)}{\partial \text{ Cov } (X_j X_k)} = o \quad \text{... (24)}$$

that is, taking the partial derivative of the variance of y with respect to the variance of X_k and the covariance of X_j and X_k, and equating to zero, respectively.

As the sample estimate of Var (X_k) is given by:

$$\text{Var}\ (X_k) = \frac{1}{n-1} \sum_k (X^2_k - n\bar{X}_k^{\,2}) \qquad \ldots\ (25)$$

$$\therefore\ \Sigma X^2_k = n\ \bar{X}_k^{\,2},\ \text{for Var}\ (X_k) = o \qquad \ldots\ (26)$$

Hence $X_k \rightarrow \bar{X}_k$ for minimum variance satisfying the partial derivative given by equation (23). Similarly, the sample estimate of the covariance is given by:

$$\text{Cov}\ (X_j X_k) = \frac{1}{n-1} \sum_{k,j} (X_j X_k - n\bar{X}_j\bar{X}_k) \qquad \ldots\ (27)$$

$$\therefore\ \Sigma X_j X_k = n\ \bar{X}_j\bar{X}_k,\ \text{for Cov}\ (X_j X_k) = o \qquad \ldots\ (28)$$

Hence $X_j X_k \rightarrow \bar{X}_j\bar{X}_k$ for minimum variance satisfying the partial derivative given by equation (24).

These criteria may be applied to model equation (16). Consider a time interval such that the values of two of the independent variables approach their respective mean values, for each set of observations,

Viz. $E_c \rightarrow \bar{E}_c$

$\Delta S \rightarrow \Delta\bar{S}$

or choose a period when the mean value of one variable becomes independent of the magnitude of the other variable, i.e. the conditional expectations of one variable's values, given the other variable, tends to a constant:

$$E\ (E_c|\Delta S) \rightarrow \text{constant} \rightarrow \bar{E}_c$$

or

$$E\ (\Delta S|E_c) \rightarrow \text{constant} \rightarrow \Delta\bar{S}$$

A similar consideration may be given to other pairs of independent variables.

By operating with the above criteria, the relationship (equation (16)) may be simplified:

(a) for an observational period with a constant evapotranspiration rate,

$$E_c \rightarrow \overline{E}_c = C_E \Delta t; \ Var\ (\overline{E}_c) \rightarrow o \qquad \ldots (29)$$

where, C_E is a constant evapotranspiration rate for Δt, the time interval $(t_1 - t_o)$.

(b) for an observational period with approximately equal changes in storage, - considering each storage component separately -

i) for baseflow:

$$\Delta S_b \rightarrow \Delta \overline{S}_b \rightarrow o; \ Var\ (\Delta \overline{S}_b) \rightarrow o$$

and

$$G_b \rightarrow \overline{G}_b = C_b \Delta t; \ Var\ (\overline{G}_b) \rightarrow o \qquad \ldots (30)$$

where, C_b is a constant baseflow rate for Δt, the time interval $(t_1 - t_o)$.

ii) for a period with constant ΔS_a (period when near maximum saturation or near complete depletion of moisture in the aeration zone can be assumed):

$$\Delta S_a \rightarrow \Delta \overline{S}_a \rightarrow o; \quad Var\ (\Delta \overline{S}_a) \rightarrow o$$

Now considering together conditions (a) and (b), the equation for surface runoff R_s may be expressed:

$$R_s = b_1 P_1 - (C_E + C_b)\ \Delta t \qquad \ldots (31)$$

If E_c and G_b cannot be estimated independently, then a general relationship between runoff and precipitation would result with regression coefficients that reflect the effect of evapotranspiration and baseflow.

In general, on a water-year basis with a carefully selected end-point, e. g. latter part of the drought season, when

$$\Delta S_b \rightarrow \Delta \overline{S}_b \rightarrow o; \ Var\ (\Delta \overline{S}_b) \rightarrow o$$

$$\Delta S_a \rightarrow \Delta \overline{S}_a \rightarrow o; \ Var\ (\Delta \overline{S}_a) \rightarrow o$$

and

$$G_r = o \text{ (assumed)}$$

the relationship may be expressed as:

$$R = b_1 P_1 - E_c \qquad \ldots (32)$$

If E_c is not estimated independently, the regression is:

$$R = b_1 P_1 + a_1 \qquad \text{... (33)}$$

in which case a regression would be the result with the effect of E_c reflected in a_1 and b_1.

Data Requirement

- historical record of the various variables.
  For an annual P-R model analysis (arranged on a yearly basis, beginning with each month), a concurrent series is required:

1 - P	4 - S_b
2 - R	5 - S_a
3 - E_c	6 - P (snowpack storage)

For monthly P-R model analysis, the following concurrent series is required:

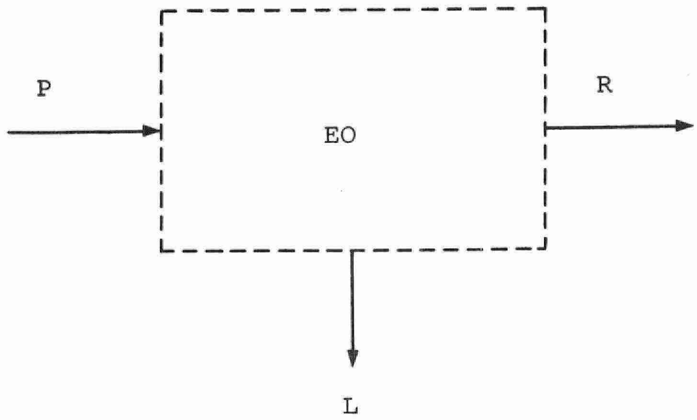
1 - P	5 - S_b (at the beginning of the month)
2 - R	6 - S_a (at the beginning of the month)
3 - E_c	7 - S_b (at the end of the month)
4 - P (snow)	8 - S_a (at the end of the month)
	9 - other meteorological parameters (temperature, humidity, radiation).

Parameter Evaluation

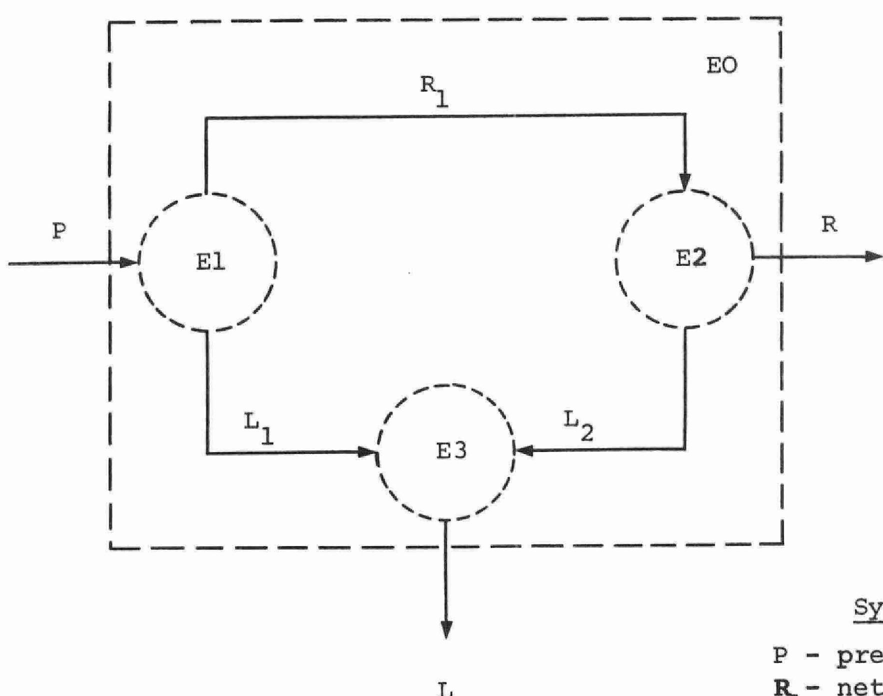
Estimates of C_1, C_2 and C_3 may be assigned from knowledge of the major soil types in the basin and their areal distribution and hydraulic and hydrologic characteristics; estimates of C_4 may be assigned from knowledge of the basin surficial geological characteristics, recharge and discharge areas and the major aquifer hydraulic and hydrologic characteristics.

The constants and the coefficients of the regression models (e.g. equations 31, 32, 33) may be determined by least-square techniques through operations in the appropriate regression sub-routines. These regression sub-routines are the result of the appropriate application of the statistical criteria for the simplification of the multiple regression models equation 16 or 17.

Whole System: One-Element Model



Whole System: Three-Element Model

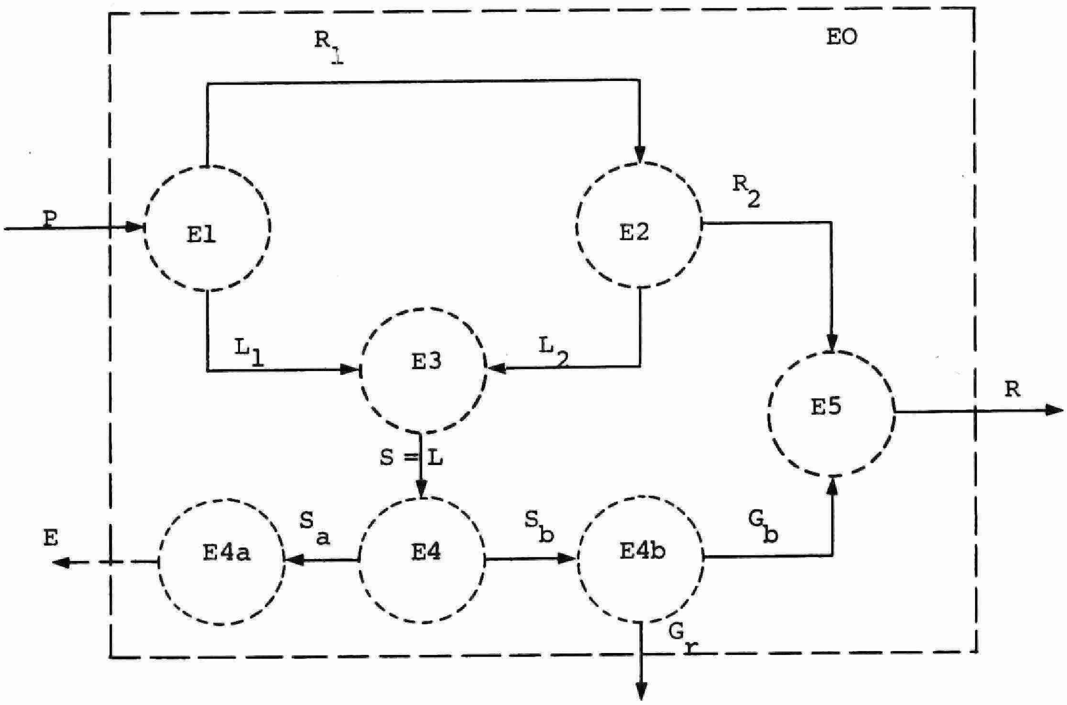


Symbols

P - precipitation
R_1 - net input
R - runoff
L, L_1, L_2 - loss
EO,..,E3 - element of the system

Figure 5a: HYDROLOGIC MODEL: A Definition Scheme for a Parametric, Linear Regression Model

Whole System: Expanded Three-Element (Multiple Element) Model



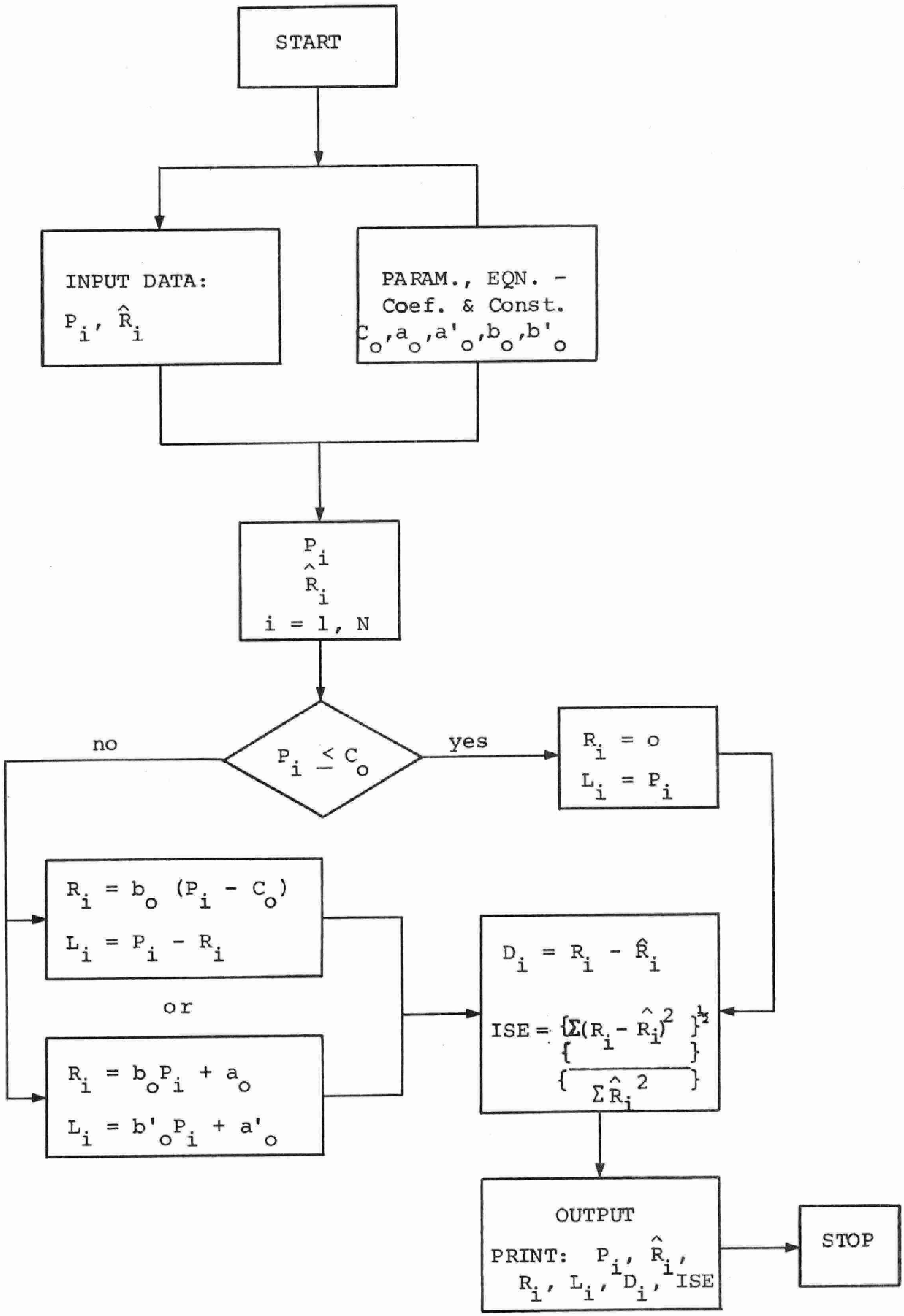
Symbols

P - precipitation
R_1 - net input
R_2, R- runoff
L_1, L_2, L - loss term
S - storage
S_a - soil moisture storage increment
S_b - ground-water storage increment
G_b - baseflow contribution
G_r - loss to regional flow
E - evapotranspiration loss
E1,...,E5 - element of the system

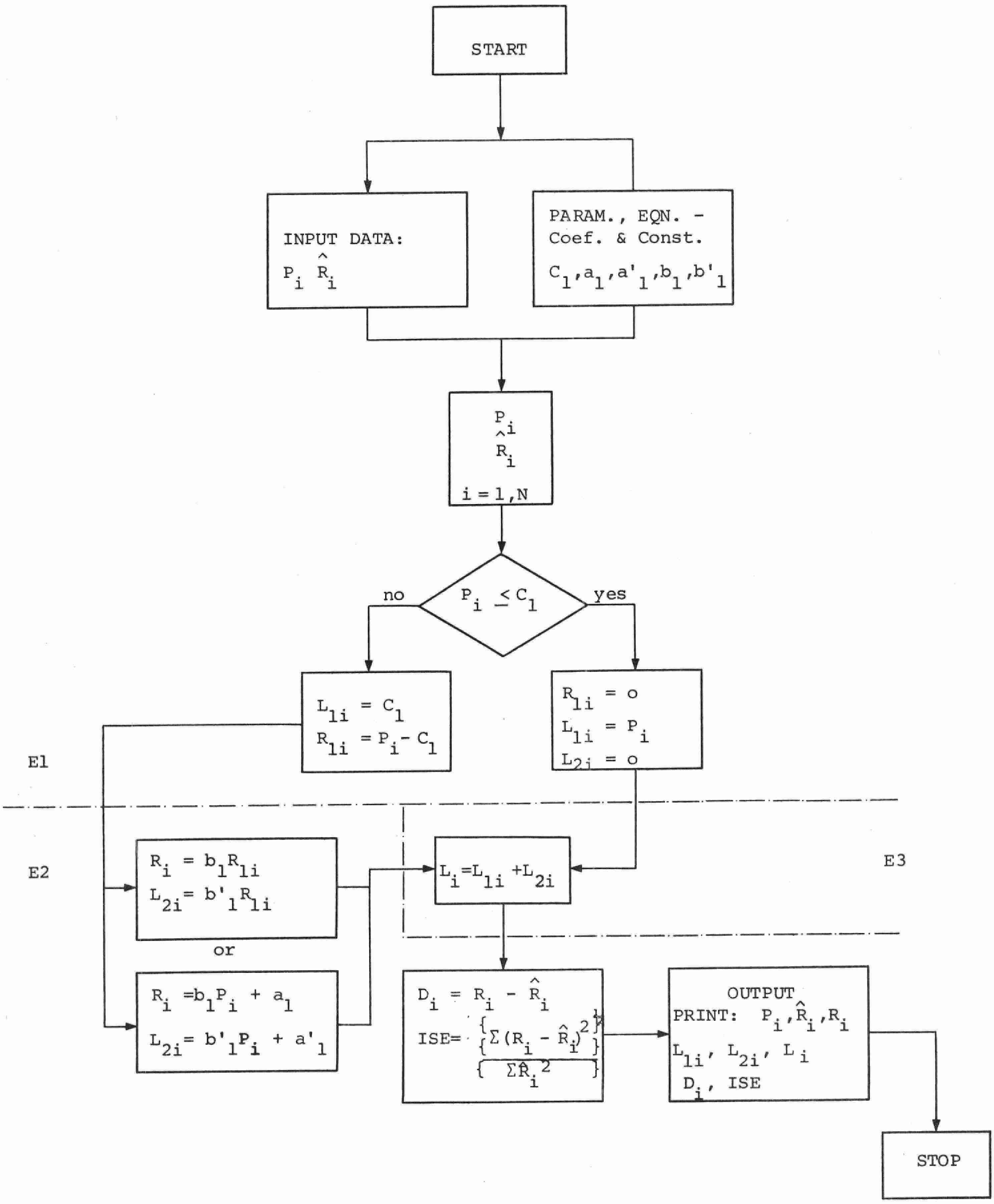
Figure 5b: HYDROLOGIC MODEL: A Definition Scheme for an Expanded, Parametric, Linear Regression Model

Figure 5c: HYDROLOGIC MODEL: Flow Chart for Parametric, Linear Regression Models

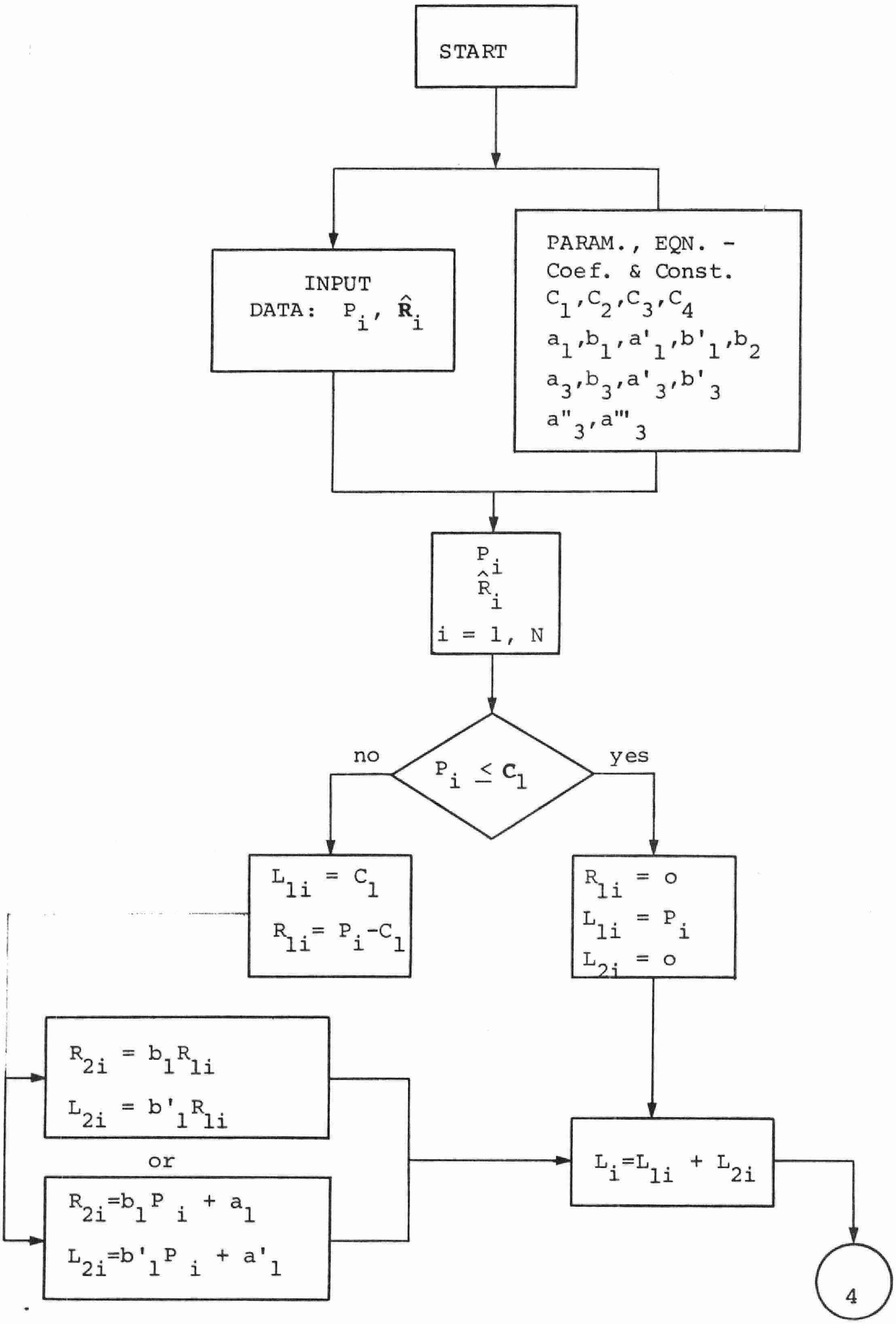
Whole System: One-Element Model, EO

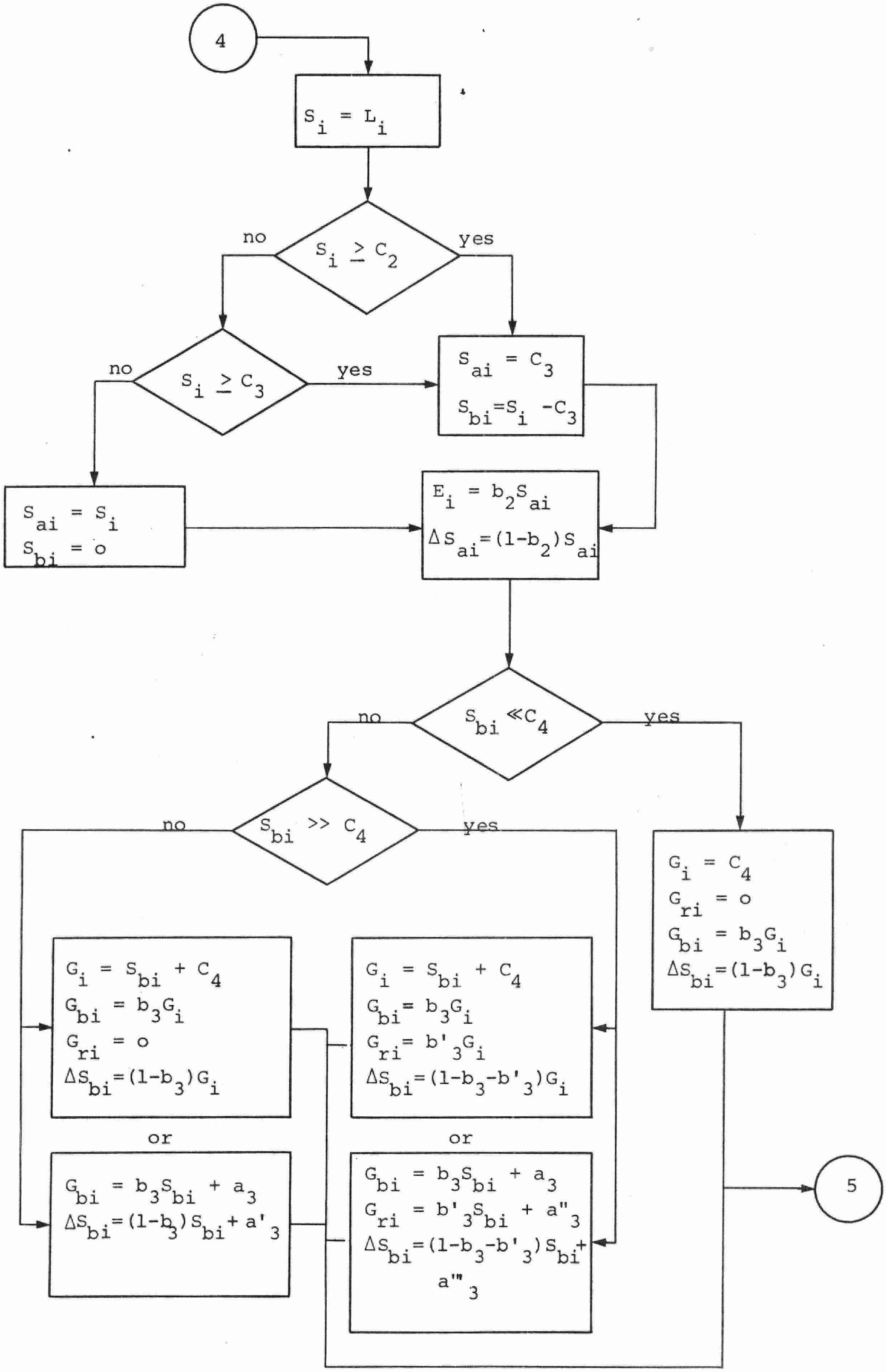


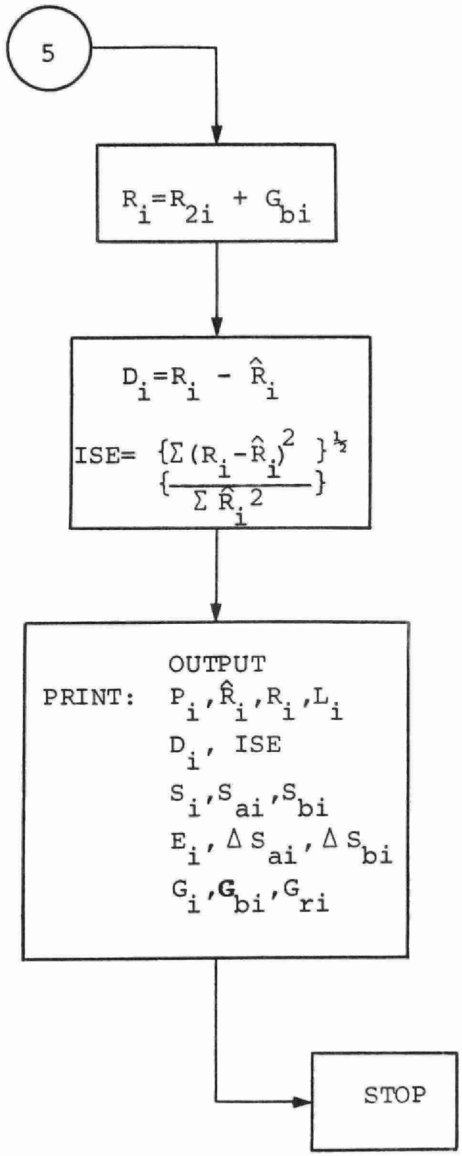
Whole System: Three-Element Model, E1,E2 & E3



Whole System: Expanded Three-Element (Multiple-Element) Model, E1, E2, E3, E4, (E4a, E4b), E5




4
S_i = L_i
no
S_i ≥ C_2
yes
no
S_i ≥ C_3
yes
S_ai = C_3
S_bi = S_i - C_3
S_ai = S_i
S_bi = o
E_i = b_2 S_ai
ΔS_ai = (1-b_2) S_ai
no
S_bi ≪ C_4
yes
no
S_bi >> C_4
yes
G_i = C_4
G_ri = o
G_bi = b_3 G_i
ΔS_bi = (1-b_3) G_i
G_i = S_bi + C_4
G_bi = b_3 G_i
G_ri = o
ΔS_bi = (1-b_3) G_i
G_i = S_bi + C_4
G_bi = b_3 G_i
G_ri = b'_3 G_i
ΔS_bi = (1-b_3-b'_3) G_i
or
or
G_bi = b_3 S_bi + a_3
ΔS_bi = (1-b_3) S_bi + a'_3
G_bi = b_3 S_bi + a_3
G_ri = b'_3 S_bi + a"_3
ΔS_bi = (1-b_3-b'_3) S_bi + a"'_3
5


5
$R_i = R_{2i} + G_{bi}$
$D_i = R_i - \hat{R}_i$
$ISE = \left\{ \frac{\Sigma (R_i - \hat{R}_i)^2}{\Sigma \hat{R}_i^2} \right\}^{1/2}$
OUTPUT
PRINT: $P_i, \hat{R}_i, R_i, L_i$
D_i, ISE
S_i, S_{ai}, S_{bi}
$E_i, \Delta S_{ai}, \Delta S_{bi}$
G_i, G_{bi}, G_{ri}
STOP

LIST OF SYMBOLS IN MODEL (FLOW CHART)

ONE-ELEMENT MODEL EO

P_i = recorded precipitation - in.
$\hat{R}_i$ = recorded runoff - in.
C_o = parameter for basin retention - in.
a_o, a'_o = regression constants
b_o, b'_o = regression coefficients
i = 1, 2, 3,....N periods of observation
R_i = computed runoff - in.
L_i = computed loss - in.
D_i = regression residual - in.
ISE = integral square error

THREE-ELEMENT MODEL E1, E2, & E3

P_i = recorded precipitation - in.
$\hat{R}_i$ = recorded runoff - in.
C_1 = parameter for basin retention - in.
a_1, a'_1 = regression constants
b_1, b'_1 = regression coefficients
L_{1i} = a loss term, from E1 - in.
R_{1i} = computed net input to E2 - in.
L_{2i} = a loss term, from E2 - in.
L_i = sum of the losses - in.
R_i = computed runoff -in.
i = 1, 2, 3....N periods of observation

MULTIPLE-ELEMENT (Expanded 3-Element) MODEL

Element E4, E4a, E4b & E5 (see definitions above plus)

S_i = storage input (= potential total losses) - in.
C_2 = a parameter for basin retention - in.
C_3 = a parameter for basin retention - in.
S_{ai} = soil moisture storage increment - in.
S_{bi} = ground-water storage increment - in.
E_i = evapotranspiration - in.

ΔS_{ai} = change in soil moisture storage - in.
C_4 = a parameter for basin storage - in.
G_i = a potential outflow increment - in.
G_{bi} = a baseflow contribution - in.
G_{ri} = loss to regional flow system - in.
ΔS_{bi} = change in baseflow storage - in.
R_{2i} = a surface runoff component - in.
R_i = computed runoff - in.
a_3, a'_3, a''_3, a'''_3 = regression constants
b_2, b_3, b'_3 = regression coefficients.

APPENDIX VI

HYDROLOGIC MODEL:

A Brief on Stochastic Models

The behaviour of a hydrologic system and/or process varies with a sequential time function. This variable process has a degree of uncertainty which can be described by probability laws and, as such, the system or process may be regarded as stochastic (an index family of random variables). That is, there is an element of chance in the values which the variables may take in the interrelated hydrological processes which define the average behaviour of the system.

Parametric hydrology generally deals with discrete hydrologic events, such as storms or floods. A parametric approach is deterministic in the sense that derived functional relationships between the input-output processes attempt to define the behaviour of the system for all times; that is, a given set of causes always produces the same set of effects. Stochastic hydrology, on the other hand, concerns itself with the time-sequential properties of the discrete events. It attempts to formulate a mathematical model for an observable phenomena which changes in time, in a way that is not completely predictable, but is expressible in terms of probabilities.

A conventional approach to stochastic hydrologic system modelling usually takes the form of a hybrid model (deterministic and stochastic). To achieve this hybrid model, a firm foundation based on the deterministic model concepts is required. The model may be used to transform the recorded series input of a variable with known or assumed probability distribution to values of an output with unknown probability distribution. Time-series analysis may then be applied to examine the generated output for its stochastic properties. Alternatively, the stochastic properties of the input variable may first be determined, then a deterministic relationship is used to transform the input to the required output. The generated output is presumed to have stochastic properties similar to that of the input variable.

Another alternative method, such as in the case where a deterministic relationship is known to exist between two time series, but cannot be specified explicitly, is to establish through regression or correlation, empirical relationships between parameters derived from statistical analyses of the individual time series. These empirical relationships are then used as a deterministic base, for the transformation procedures.

A more aggressive approach (Chow & Kareliotis) to stochastic hydrologic system modelling, Figure 6, is to formulate a stochastic

model for the hydrologic system in which runoff is considered as the integral of three component stochastic processes, viz., change in conceptual watershed storage, the total rainfall input and the total watershed losses, mainly evapotranspiration. In the analysis, the integrated stochastic processes are treated as a three-dimensional vector or multiple-time series with each time series consisting of a deterministic and a random component.

The mathematical notation given for each stochastic process in Figure 6 is called a time series. For example the set of observations $(P\ (t);\ t \in T)$ is called a time series for precipitation; i.e. for each t in T the observation P (t) is an observation of the random variable. Prior to analyzing the time series, it is necessary to assume a model for the stochastic process, e. g. moving average, MA, harmonic, H, auto-regression, AR, or Markov Chain, MC. Standard statistical techniques in time-series analyses (correlogram and spectral density analysis) aid in the identification of the model inherent in the data sequence, through goodness of fit tests on the assumed model by comparing generated output with historical data sequences.

Precipitation - Simulator

- available data - historical, discrete time series:
  $\{P\ (t);\ t\ \epsilon T\}$
- assume that $\{P\ (t);\ t\ \epsilon T\}$ is a stochastic process
- assume a type of model (moving average, harmonic, or Markov Chain, etc.)
- analyse time series (correlogram or spectral density analysis)
- identify and choose appropriate simulator (Model).

Evapotranspiration - Simulator

- available data - computed estimates, discrete time series:
  $\{E\ (t);\ t\ \epsilon T\}$
- assume that $\{E\ (t);\ t\ \epsilon T\}$ is a stochastic process
- assume type of model
- analyse time series
- identify and choose appropriate simulator.

Conceptual Watershed Storage - Simulator

- available data - computed estimates, discrete time series:
  $\{S\ (t);\ t\ \epsilon T\}$
- assume that $\{S\ (t);\ t\ \epsilon T\}$ is a stochastic process
- assume type of model
- analyse time series
- identify and choose appropriate simulator.

Transformation System

- assume multiple time series:
  $\{P(t),\ E(t),\ S(t),\ R(t);\ t\ \epsilon T\}$
- assume that the multiple time series is a stochastic process
- assume type of model (mass balance):

$S(t + 1) - S(t) = P(t) - R(t) - E(t)$ or
$E(t) = P(t) - R(t) - (S(t + 1) - S(t))$ or
$R(t) = P(t) - E(t) - (S(t + 1) - S(t))$

- optimize model parameters.

Runoff - Simulator

- available data - historical, discrete time series:
  $\{R\ (t);\ t\ \epsilon T\}$
- assume that $\{R\ (t);\ t\ \epsilon T\}$ is a stochastic process
- assume type of model
- analyse time series
- identify and choose appropriate simulator.

Notations:

P (t) - Precipitation observation
E (t) - Evapotranspiration observation
S (t) - Conceptual watershed storage
R (t) - Total runoff observation
t ϵT - Denotes the discrete time t, belongs to (sub-set) of an interval of real time T;
$T = o \leq t \leq L$
where L is the length of the time interval.

Figure 6. HYDROLOGIC MODEL: A Schematization for a Type of Stochastic Hydrologic System Model.

Latitude 44° 28′

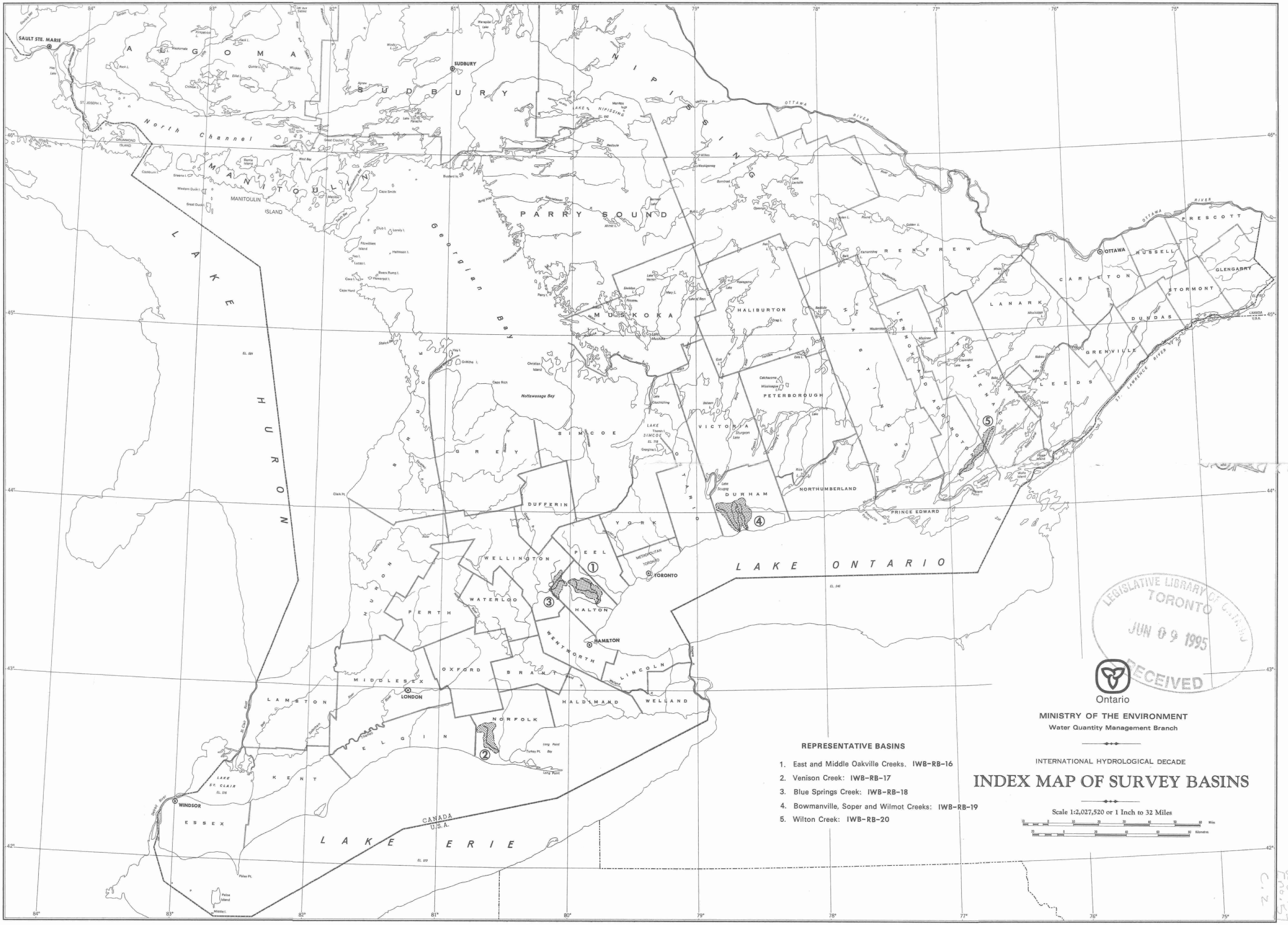
Longitude 76° 56′

Longitude 76° 37′

Latitude 44° 10′

LEGEND

Hydrometric station, natural control, recording	NR
Hydrometric station, natural control, non-recording	NN
Hydrometric station, artificial control, recording	AR
Hydrometric station, artificial control, non-recording	AN
Water level gauge	WG
Water temperature station	WT
Water quality station	WQ
Sedimentation station	SD
Groundwater well, recording	GR
Groundwater well, non-recording	GN
Piezometer (asterisk replaced by number of piezometers in nest)	P*
Snow course	SC
Snow gauge	SG
Snow stake	SS
Precipitation gauge, recording	PA
Precipitation gauge, non-recording	PN
Rain gauge, recording	RA
Rain gauge, standard	RS
Hygrothermograph	HT
Hygrometric station	HY
Anemometer (asterisk replaced by height above ground, in meters)	A*
Radiometer	SN
Sunshine recorder	SR
Evaporation station	ES
Soil moisture site	SM
Soil temperature site	ST
Tritium concentration in air	TC
Air temperature	AT



REPRESENTATIVE BASINS

1. East and Middle Oakville Creeks. IWB-RB-16
2. Venison Creek: IWB-RB-17
3. Blue Springs Creek: IWB-RB-18
4. Bowmanville, Soper and Wilmot Creeks: IWB-RB-19
5. Wilton Creek: IWB-RB-20

Ontario

MINISTRY OF THE ENVIRONMENT

Water Quantity Management Branch

INTERNATIONAL HYDROLOGICAL DECADE

INDEX MAP OF SURVEY BASINS

Scale 1:2,027,520 or 1 Inch to 32 Miles

MAP 4002-1

Latitude 44° 05′

Longitude 78° 53′

Longitude 78° 30′

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BOWMANVILLE, SOPER and WILMOT CREEKS DRAINAGE BASIN

SOUTHERN ONTARIO

MAP 4724-4

BASIN INSTRUMENTATION SEPTEMBER 1972

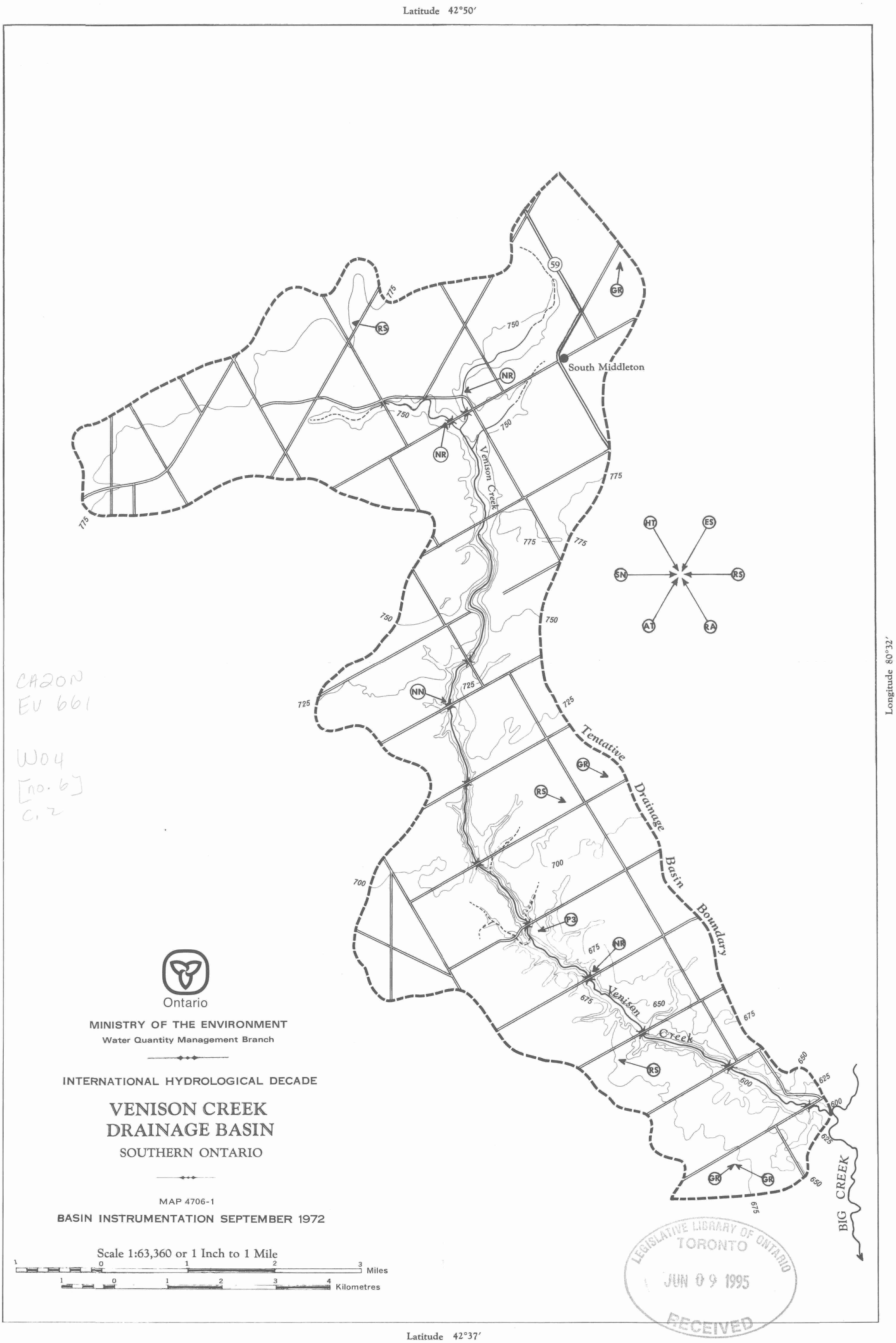
Scale 1:63,360 or 1 Inch to 1 Mile

Miles 1 0 1 2 3 4

Kilometres 1 0 1 2 3 4 5

Note: Drainage Basin Boundaries are tentative only.

Latitude 43° 52′



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VENISON CREEK DRAINAGE BASIN

SOUTHERN ONTARIO

MAP 4706-1

BASIN INSTRUMENTATION SEPTEMBER 1972

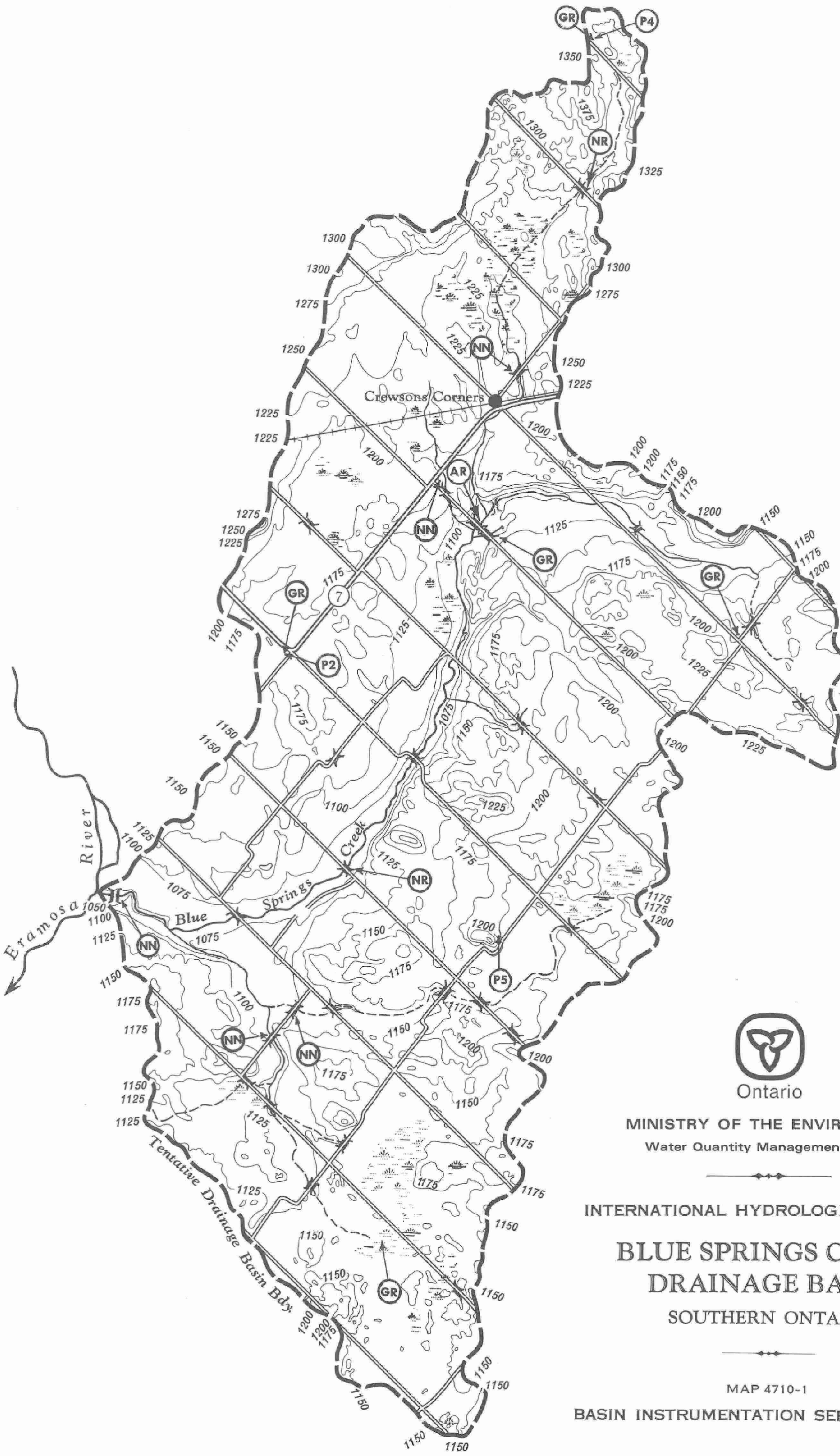
Scale 1:63,360 or 1 Inch to 1 Mile

Miles 1 0 1 2 3

Kilometres 1 0 1 2 3 4

Latitude 43°42′

Longitude 80°10′



Ontario

MINISTRY OF THE ENVIRONMENT

Water Quantity Management Branch

INTERNATIONAL HYDROLOGICAL DECADE

BLUE SPRINGS CREEK DRAINAGE BASIN

SOUTHERN ONTARIO

MAP 4710-1

BASIN INSTRUMENTATION SEPTEMBER 1972

Scale 1:63,360 or 1 Inch to 1 Mile

Miles 1 0 1 2 3

Kilometres 1 0 1 2 3 4

Note: M of E instrumentation only

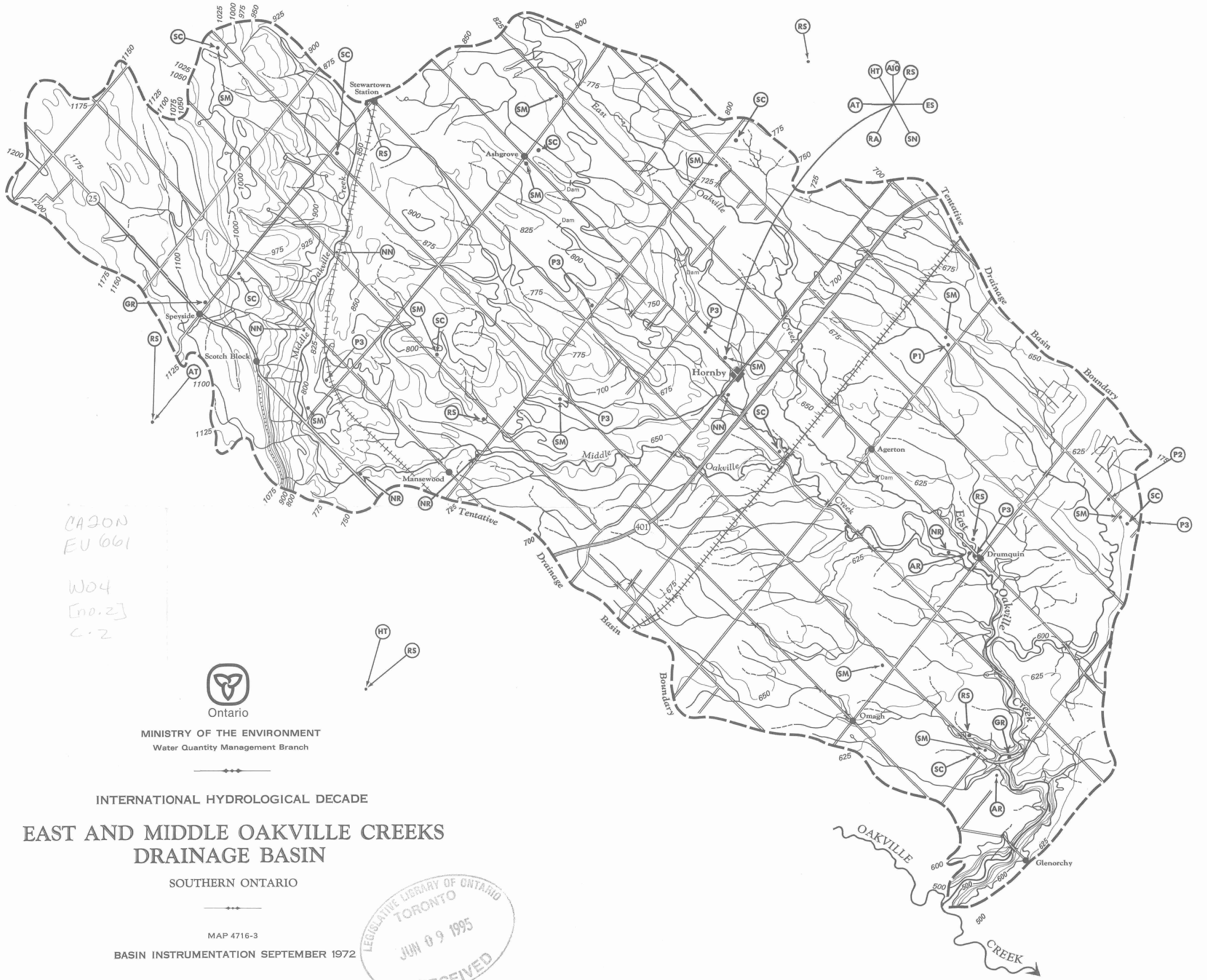
Longitude 80°00′

Latitude 43°30′

Latitude 43° 39′

Longitude 80° 02′

Longitude 79° 43′



Ontario

MINISTRY OF THE ENVIRONMENT

Water Quantity Management Branch

INTERNATIONAL HYDROLOGICAL DECADE

EAST AND MIDDLE OAKVILLE CREEKS DRAINAGE BASIN

SOUTHERN ONTARIO

MAP 4716-3

BASIN INSTRUMENTATION SEPTEMBER 1972

Scale 1:63,360 or 1 Inch to 1 Mile

Miles 1 0 1 2 3 4

Kilometres 0 1 2 3 4 5 6

Latitude 43° 27′

96936000009287